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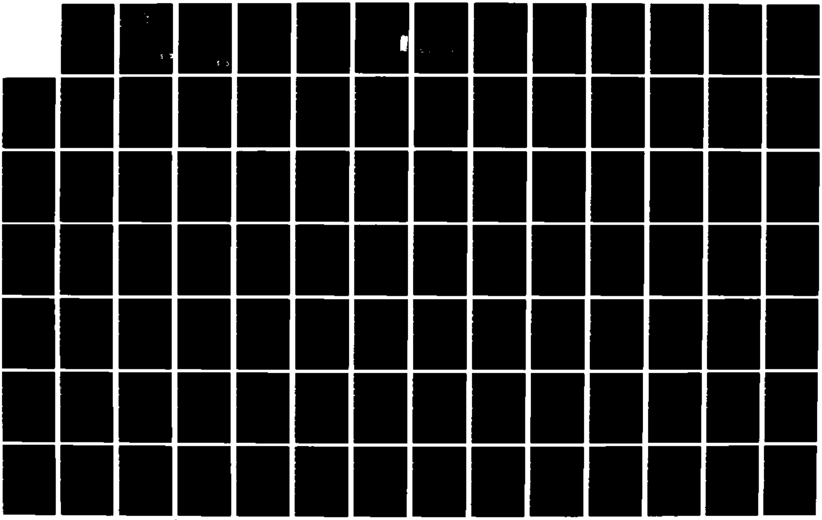

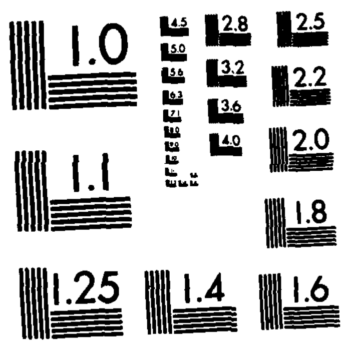

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A SPARES STOCKAGE ALGORITHM
FOR LOW-DENSITY EQUIPMENT

George C. Pankonin, Captain, USAF
David K. Peterson, Captain, USAF

LSSR 33-82

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Current U.S. Air Force stockage models are generally demand driven, performing satisfactorily for spares which have high usage rates. However, critical end-items such as automatic test equipment are characterized by very low spares usage rates. Consequently, current stockage policies typically do not stock spares for these end-items. This model has two unique features. First, It pools and averages demand data from bases supporting similar end-items to obtain a more precise usage rate estimate of infrequently demanded spares. Secondly, the model allows the consideration of two resupply priorities and durations rather than the single mean resupply time which many current inventory models assume. This allows the model to explicitly deal with priority transportation for mission critical requirements. The algorithm was applied to spares usage data for the F-15 Avionics Intermediate Shop Displays Test Station provided by Headquarters Tactical Air Command. The model provides a cost-effective purchase sequence for low-demand spares. Using the model, the manager may base stockage decisions upon: (1) system availability, (2) total budget, or (3) an implied stockage penalty cost. The study demonstrated that: (1) purchases recommended early in the purchase sequence dramatically increase system availability for a relatively low spares investment, and (2) the current stockage policies recommend an inefficient inventory investment.

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A SPARES STOCKAGE ALGORITHM
FOR LOW-DENSITY EQUIPMENT

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

By

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September 1982

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Captain George C. Pankonin

and

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has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

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CHAPTER I

INTRODUCTION

Background

Air Force Manual 1-1, Functions and Basic Doctrine of the United States Air Force, states:

> The mission of the United States Air Force is to prepare our forces to fight to preserve the security and freedom of the people of the United States. Our goal is peace. To achieve this goal we must deter conflict by maintaining a force that is capable and ready [Ref 31:v].

In recent years these preparations have emphasized attaining the needed capability at the expense of sustainability. The result, according to the Air Force Deputy Chief of Staff for Logistics and Engineering, Lt Gen Billy M. Minter, was a very capable force sustainable only for a short time (Ref 30:42-43).

This limited sustainability restricts the operational readiness of a weapon system. Operational readiness measures a weapon system's ability to perform its assigned mission (Ref 21:495). Operational availability is the percentage of time that a system is operationally ready (Refs 24:15; 25:16).

Logistics is the process whereby systems are acquired, supported, and maintained operationally ready (Ref 21:401). Traditionally, defense planning focused upon

force size and modernization, expecting the logistical support to be available when needed (Ref 15:3). General Minter believed: "If the U.S. does go to war, it's likely to be a come-as-you-are situation, so the logistics end of things will have to be ready to go [Ref 30:42-43]." Thus "our pr . concern is getting the spares levels up to meet the requirement. We are woefully short of spares. . . [Ref 30:43]." The availability of spare parts is critical to the day-to-day operational availability of a weapon system (Ref 15:3). Two of the primary measures of asset availability are:

1. The number of end items not mission capable due to supply (NMCS).

2. The inventory stockage effectiveness or ready rate.

The NMCS rate is the proportion of aircraft at any unit incapable of performing their mission due to the lack of necessary spares. An inventory's stockage effectiveness is the proportion of customer demands satisfied from on-hand assets.

A spare part's availability is driven by two basic inventory decisions, the range and depth of items stocked (Ref 11:18). "The biggest job for Air Force logisticians and engineers today is to identify the support requirements and program for the necessary funding [Ref 30:44]." In fiscal year (FY) 1981, the acquisition of spare parts

was reemphasized. This new emphasis upon spares acquisition continues:

> The Air Force's FY 1982 aircraft spares procurement budget is well over a billion dollars higher than in FY 1981. Furthermore, the Air Force spares procurement that was programmed for fiscal years 1982, 83, and 84, is about $600-700 million per year higher than was programmed for those same years as recently as January 1980 [Ref 15:3].

With the increased allocation for spares purchases comes an additional responsibility to manage the funds wisely. The forecast of increasing federal deficits in fiscal years 1983 and 1984 reemphasizes the Air Force's need to carefully manage its increased spares funding (Ref 27:50).

One challenge for inventory system managers is meeting unknown future requirements. Another is "to acquire the capability to link resource inputs to an estimate of the equipment availability [Ref 15:6]." This capability is particularly important when preparing and justifying year-end budgets (Ref 15:6). In general, future inventory models need to be able to compute the least cost, most efficient mix of spares for any given level of availability (Ref 25:17).

Virtually every system would benefit from increased spares support. Automatic Test Equipment (ATE) is no exception. ATE are:

> Electronic devices capable of automatically or semiautomatically generating and independently furnishing programmed stimuli, measuring selected parameters of an electronic, mechanical or electromechanical item being tested and making a comparison to accept or reject the measured values according to predetermined limits [Ref 21:80].

The specific ATE studied was the $3.2 million Displays Test Station, a significant component of the $16.2 million F-15 Avionics Intermediate Shop (AIS) (Ref 14). This system was representative of other Air Force ATE, highly reliable and assigned in limited numbers to any base. The AIS fault testing capability permits intermediate, base-level maintenance. Thus, fewer spares are required to achieve a given level of weapon system availability. In effect, the intermediate repair capability becomes a spares multiplier, increasing a base's self-sufficiency (Ref 3).

The advantages of reduced spares requirements and enhanced self-sufficiency result from a high AIS operational availability. Yet, Tactical Air Command's (TAC) Displays Test Station FY 1981 operational availability rate was approximately 85 percent (Ref 28). Highly reliable equipment, such as the Displays Test Station, often receive lower component spares stockage. The more reliable the component is, the less often it is stocked. Therefore, the eventual failure of any highly reliable component can render the test station inoperable.

Problem Statement

Current Air Force inventory policies determine the range and depth of stockage based upon experienced item demands. These models adequately support items which have constant and relatively frequent demand patterns. However, the stockage position recommended for infrequently demanded items may not yield adequate weapon system availability. Current policies do not provide the decision maker a means to relate inventory stockage to equipment availability. Asset stock levels at any individual base, computed by these models, are independent of demand patterns experienced by other bases supporting similar weapon systems.

Research Objectives

This research had four main objectives. First, develop an alternative inventory algorithm versus current Air Force inventory policies, focusing on the requirements of low-demand, high-reliability equipment. Second, provide the means to predict weapon system availability given specific levels of inventory investment. Third, list the most cost-effective inventory purchases given any desired availability or budget level. Fourth, apply the algorithm to actual data derived from an operational Air Force system.

Research Questions

This study was intended to answer three general research questions.

First, what would a cost-effective stockage policy for low-density, high-reliability items be?

Second, how would a cost-effective stockage policy compare with current stockage policies used by the Air Force?

Third, how sensitive would a cost-eıfective stockage policy be to data variations?

Scope

This study concerned the base level stockage of spares. The model was designed for items that experienced extremely low demand rates; on the order of one demand per base per year.

Determining the depth of stock was not the model's primary purpose. Rather, the appropriate question involved deciding whether to stock one or none of an item.

The F-15 AIS Displays Test Station provided the study's data base due to its typical ATE characteristics. However, the algorithm would be applicable for any high-reliability, low-density system.

Overview

This chapter briefly introduced the purpose of maintaining inventories, and the problems of measuring

inventory effectiveness and predicting future inventory performance. A problem statement was formulated, and a list of objectives toward resolving the problem were detailed. Finally, the research questions were posed. Chapter II presents a review of related inventory literature; Chapter III outlines the research methodology; Chapter IV presents the results of operating and testing the algorithm; and Chapter V summarizes the research, forms conclusions from the results and recommends areas for future research.

CHAPTER II

LITERATURE REVIEW

Introduction

Modern inventory theory is marked by the duality of its issues. Commonly, items of inventory are classified as either expendables or recoverables. Coincidentally, there are two primary inventory management approaches, deterministic and probabilistic. Combinations of these classes and approaches form the spectrum of inventory management techniques which seek answers for two critical questions:

1. What range of items should be stocked?
2. How deep should the stock be?

Definitions

Expendables are typically low-cost items which are consumed in use. Usually, failed expendables are physically or economically infeasible to repair. Expendables lose their self-identity when installed on higher assemblies. Nails, paint, and pencils are common expendables.

Recoverables are typically high-cost items which are not consumed in use. Failed recoverables are usually mechanically and economically feasible to repair. They

retain their self-identity when in use, and are items such as radios or radar units. Recoverables are also known as repairables or repair cycle assets.

The two basic inventory management approaches differ in the certainty they ascribe to input variables. Deterministic approaches assume all input variables are known with certainty. Probabilistic approaches introduce an element of chance into their variable values.

Scope

First, the touchstone for modern probabilistic inventory theory, Palm's Theorem, will be presented. Next, five common inventory performance predictors are reviewed. Third, the Air Force approaches for managing expendables and recoverables are presented. Finally, seven probabilistic inventory models are reviewed.

Palm's Theorem

In 1943, Cornelius Palm presented a paper which became the foundation for many modern probabilistic inventory theories (Ref 8:1). He demonstrated that the number of units in a multiple server queueing system with slack capacity could be found given that:

1. The arrival of units to the system was Poisson distributed with a mean λ.

2. The time a unit remained in service was independent of arrivals, and other units in the system.

3. The mean time a unit spent in service (T) was known (Ref 8:5).

Palm's Theorem predicted that the expected number of units (x) in the system at any time was (Ref 8:6):

$$E(x) = \lambda T \qquad \text{(Eq 1)}$$

The probability that exactly x units were in the system was (Ref 8:7):

$$p(x) = \frac{e^{-\lambda T}(\lambda T)^{x}}{x!} \qquad \text{(Eq 2)}$$

Palm's Theorem required only that the mean time a unit remained in the system was known exactly; the expected number of units in the system was independent of the probability distribution about T (Ref 8:8). However, the expected number of units in the system was sensitive to changes in the T value (Ref 8:27). Palm's Theorem evolved into the basis for computing the expected number of backorders, and the probability of assets in resupply, used in many inventory models.

Performance Measures

There are five common inventory system performance measures: (1) fill rate, (2) ready rate, (3) average backorders, (4) operational rate, and (5) average NMCS (Ref 6:1). An inventory system's characteristics and objectives determine which measure it employs. Performance

measures and predictors provide the means to compare and adapt inventory techniques to specific situations.

Four assumptions, and Palm's Theorem, are required to predict the behavior of individual inventory items:

1. Stock replenishment requests are not bunched. For every demand placed upon supply, a stock replenishment requisition is immediately sent to the depot. In the Air Force, this is true of recoverable items and infrequently demanded expendable items.

2. All demands are either satisfied from on-base stock, or are backordered to the depot.

3. The number of demands occurring per time interval is stationary about a mean (λ), and varies proportionately with the interval's length.

4. The period of time required for resupply is stationary about a mean (T), and is independent of the demand frequency (Ref 6:7).

Under these assumptions, a Poisson probability distribution (Eq 2) may represent the probability of exactly x units being in resupply at any time. Thus, Palm's general queueing model is modified for inventory management (Ref 6:8).

Fill Rate

An item's fill rate is the percentage of demands satisfied from on-hand stock (Ref 6:2). The fill rate

is directly proportional to the amount of time that the quantity of item i available is positive (Ref 6:10). On-hand stock is positive only when the number of assets in resupply (r_i) is less than the quantity of authorized stock(s). The fill rate (FR) is (Ref 6:11):

$$FR_i = \sum_{r_i=0}^{s_i-1} p(r_i|\lambda_i T_i) \qquad \text{(Eq 3)}$$

Ready Rate

The ready rate (RR) is slightly different from fill rate. Ready rate is the percent of time that no backorders exist (Ref 6:11). It is proportional to the amount of time that on-hand stock is greater than, or equal to zero. The ready rate is found with (Ref 6:12):

$$RR_i = \sum_{r_i=0}^{s_i} p(r_i|\lambda_i T_i) \qquad \text{(Eq 4)}$$

Average Backorders

A backorder (B) occurs when the number of assets in resupply exceeds the amount of authorized stock (Ref 29:14):

$$B_i = r_i - s_i \qquad \text{(Eq 5)}$$

The average or expected number of backorders is (Ref 29:14):

$$E(B_i) = \sum_{r_i=s_i+1}^{\infty} (r_i - s_i)\, p(r_i | \lambda_i T_i) \qquad \text{(Eq 6)}$$

Average backorders offers the advantage of accounting for both the occurrence and duration of a backorder (Ref 6:2).

Operational Rate

The probability that at any random time there are no base-level backorders is the operational ready rate (OR) (Ref 6:3). If an inventory stocks all parts essential to a fully operational aircraft, then the OR rate is the probability that no aircraft is NMCS (Ref 6:3-4). However, the OR rate does not differentiate between the number of NMCS aircraft; having one NMCS aircraft is considered as critical as several NMCS aircraft (Ref 6:4).

The probability that no backorders exist for the entire range of items (n) is (ref 6:12):

$$OR = \prod_{i=1}^{n} RR_i \qquad \text{(Eq 7)}$$

Combining (eq 4) and (eq 7), the OR rate becomes (Ref 6:12):

$$OR = \prod_{i=1}^{n} \sum_{r_i=0}^{s_i} p(r_i | \lambda_i T_i) \qquad \text{(Eq 8)}$$

Cannibalization is the process of consolidating backorders on the smallest possible number of

end-items (Ref 21:107). When cannibalization is allowed, an NMCS aircraft becomes an additional source of spares (except for the broken item). Thus, available base stock is augmented by the quantity per application (QPA) of each item installed on the aircraft. The OR rate, with k NMCS aircraft available for cannibalization, becomes (Ref 6:13):

$$OR_k = \prod_{i=1}^{n} \sum_{r_i=0}^{s_i+(k \cdot QPA)} p(r_i | \lambda_i T_i) \qquad \text{(Eq 9)}$$

The OR rate directly relates the supply system's effectiveness to mission readiness (Ref 6:3).

Average NMCS

The average number of NMCS aircraft during any specified time interval is Average NMCS (Ref 6:4). Methods used to estimate Average NMCS assume that any item backordered will ground an aircraft. Also, a cannibalization policy must be specified; for example, either none or complete (Ref 6:13).

When cannibalization is allowed, the probability of zero NMCS aircraft is the OR rate with zero cannibalized aircraft (Refs 6:14; 10:16):

$$P(0\ NMCS) = OR_{k=0} = \prod_{i=1}^{n} \sum_{r_i=0}^{s_i} p(r_i | \lambda_i T_i) \qquad \text{(Eq 10)}$$

The probability of one or fewer NMCS aircraft is the OR rate with one NMCS aircraft (Ref 6:14). Therefore, the probability of exactly one NMCS aircraft is (Ref 10:16):

$$P(1\ \text{NMCS}) = OR_{k=1} - OR_{k=0} \qquad \text{(Eq 11)}$$

Knowing the exact individual probabilities, the average number of NMCS aircraft for a squadron with N aircraft is (Refs 6:15; 10:16):

$$E(\text{NMCS}) = \sum_{k=0}^{N} kp(k) \qquad \text{(Eq 12)}$$

If cannibalization is not allowed, the Average NMCS can be found if the number of backorders for an item is known. Under this policy, the probability that a random aircraft is missing item i is (Ref 18:55):

$$\frac{B_i}{N} \qquad \text{(Eq 13)}$$

If the exact backorder number is unknown, the expected number of backorders (Eq 6) may be substituted. The probability that an aircraft is not missing item i is (Ref 18:49):

$$p(i|s_i) = \left(1 - \frac{E(B_i)}{N \cdot QPA_i}\right)^{QPA_i} \qquad \text{(Eq 14)}$$

An aircraft is available when no items are missing; thus, the probability an aircraft is available (PAA) is (Ref 18:45):

$$PAA = \prod_{i=1}^{n} \left(1 - \frac{E(B_i)}{N \cdot QPA_i}\right)^{QPA_i} \qquad \text{(Eq 15)}$$

The expected number of NMCS aircraft is (Ref 10:18):

$$E(NMCS) = N - (PAA \cdot N) \qquad \text{(Eq 16)}$$

Air Force Inventory Management

The Air Force uses two different models to manage expendables and recoverables. At the base-level, inventory management is automated and processed by the UNIVAC 1050-II computer. In December 1981 the expendable model was changed from a strictly demand driven to cost-balancing technique (Ref 11:21). The recoverable or repair cycle model has remained constant in recent years.

Air Force Expendable Management

For expendables, the range of stock is based upon demand and cost analysis, the depth of stock upon economic order quantity theory (Ref 11:18). The model requires eight different cost variables:

1. The item's unit price (C_p)
2. The routine resupply ordering cost (C_o), fixed at $4.54.

3. The inventory holding cost rate (C_h), valued at 26 percent of unit cost.

4. The cost to add an item to inventory (C_a), fixed at $3.38.

5. The cost to maintain stock (C_m), fixed at $11.20.

6. The backorder cost (C_b), fixed at $2.55.

7. The cost to expedite priority backorders (C_x), fixed at $6.47.

8. The variable shortage cost factor (C_s) (Ref 11:19).

The shortage cost factor is determined by an item's stockage priority code (SPC) (Ref 11:19). The SPC reflects the priority which is used at base level to requisition an item:

SPC	Cause	C_s Value
1	NMCS Incident	$35.00
2	Mission Critical	25.00
3	Mission Impaired	10.00
4	Routine Requirement	4.00

The desired availability (α) for any item is fixed at 90 percent (Ref 11:19). The item essentiality factor (E) will allow future weighting of item essentiality, and is currently fixed at one (Ref 11:19).

Range Determination

Three costs are computed to determine the range of stock: (1) the cost of not stocking (C_{ns}), (2) the cost-to-stock (C_{st}), and (3) the cost-to-retain stock (C_r) (Ref 11:19-20). The cost of not stocking an item is:

$$C_{ns} = D_d \, [(E \cdot C_s \cdot \lambda) + C_x] \qquad \text{(Eq 17)}$$

where D_d is the mean daily demand (daily demand rate) (Ref 11:20). The cost-to-stock is stated as (Ref 11:20):

$$C_{st} = C_a + C_r \qquad \text{(Eq 18)}$$

Finally, the cost-to-retain an item in inventory is:

$$C_r = C_m + [R-(D_d \cdot \lambda) + \frac{Q}{2}](C_h \cdot C_p) + (\frac{D_d}{Q} \cdot C_o)$$

$$+ D_d(1-\alpha)(E \cdot C_s \cdot \lambda \cdot C_b) \qquad \text{(Eq 19)}$$

where R is the reorder point, and Q is the economic order quantity (Ref 11:20). The range decision logic compares the cost-of-stocking with the cost of not stocking, and selects the least costly alternative (Ref 11:21).

Depth Determination

The stockage depth is found using a variation of Wilson's economic order quantity (EOQ) formula (Ref 11:21). The basic EOQ formula seeks the order quantity, for a single item, that minimizes total inventory holding and

ordering costs (Ref 21:246). The depth of stock is found with:

$$Q = \frac{Y\sqrt{D_d \cdot C_p}}{C_p} \qquad \text{(Eq 20)}$$

where (Refs 11:21; 33:11-13):

$$Y = \sqrt{\frac{2\ C_o}{C_h}} \qquad \text{(Eq 21)}$$

Air Force Recoverable Management

The repair cycle is a term used to describe Air Force recoverable inventory management. The repair cycle may be pictured as a flow of parts between end-items, repair and supply facilities. It oper[illegible]s at, and between, the base and depot levels.

The repair cycle begins with the failure of an installed asset (Figure 1). Base maintenance removes the unserviceable item and requests a replacement from base supply. Maintenance also begins to repair the failed asset. The number of assets repaired on-base divided by the total number of asset failures is the percent of base repair (PBR). The time required to repair an asset and return it to inventory is the repair cycle time (RCT).

If the unserviceable item cannot be repaired on-base it is returned to the depot for repair. In this case, base supply submits a stock replenishment request

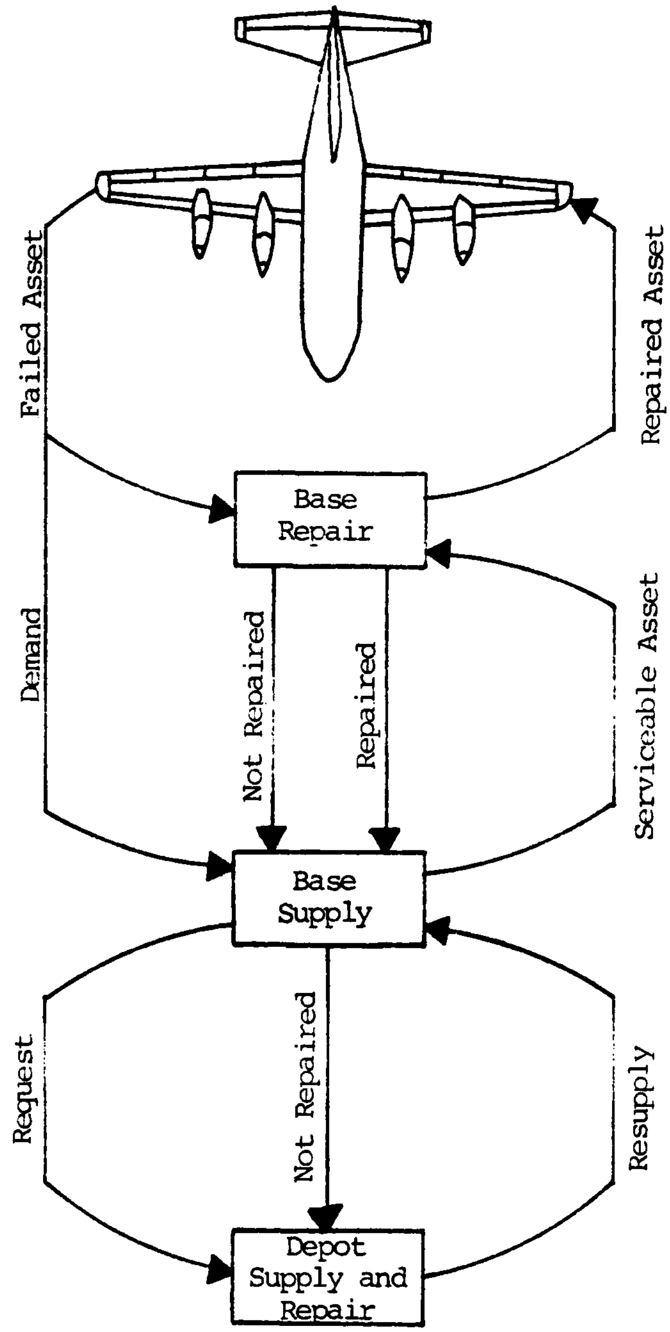

Fig. 1. The Repair Cycle

to the depot, for a like item, to maintain the authorized base spares inventory.

Model Assumptions

The repair cycle model makes three crucial assumptions. First, it assumes all items are equally essential. Second, the daily demand rate is assumed to be stationary. Finally, serviceable parts are assumed to always be available at the depot.

Model Formulation

The depth of stock needed to fill the base repair cycle pipeline (Q_p) is:

$$Q_p = (D_d)(PBR)(RCT) \qquad \text{(Eq 22)}$$

Combining the base and depot repair cycle pipelines, the equation expands to:

$$Q_p = D_d[(PBR)(RCT) + (1-PBR)(OST)] \qquad \text{(Eq 23)}$$

where OST is the order and shipping time between base and depot. One minus the percent of base repair represents the fraction of depot-level repairs. A safety stock (SS) is computed to account for uncertainty in the variable estimates:

$$SS = \sqrt{3Q_p} \qquad \text{(Eq 24)}$$

The safety stock is estimated to provide an 84 percent ready rate.

The total base authorized stock (Q_B) is:

$$Q_B = Q_p + \sqrt{3Q_p} + C_{pa} \qquad \text{(Eq 25)}$$

where C_{pa} is the unit price adjustment factor. The adjustment factor is 0.9 if the unit cost is less than $750.00, and 0.5 otherwise. The adjustment factor is used in rounding down to the next whole integer when computing Q_B (Ref 33:11-13).

Model Critique

The repair cycle model has three main weaknesses. First, since the model is demand-driven, inventory operating costs are ignored. The cost-benefit ratio of stocking is not considered. Second, although the safety stock is designed to provide an 84 percent ready rate, no measure of weapon system availability is provided. Finally, an item is only considered for stockage once it experiences two or more demands in a calendar quarter (Ref 33:11-14).

Base Stockage Model

This model developed a base-level stockage policy for recoverables which considered the level of system support provided by varying levels of inventory investment (Ref 12:3). The model allowed inventory managers to select

stock levels that achieved a desired fill rate, or to maximize the inventory fill rate given a fixed inventory investment (Ref 12:3-4).

Demands

Earlier studies found that most recoverable spares experienced low demand rates; typically, these rates were less than five units per month (Ref 12:6,11). Demand variability was high for most spares, and "could only be explained by long periods of zero demand followed by occasional high or peak demands [Ref 12:6]."

A study of recoverable spares at Andrews AFB, Maryland from October 1961 to April 1962 found the following demand frequencies:

Number of Demands	Percent of Recoverable Inventory
0	73.7%
1	11.3
2	4.8
3	2.8
4	2.0
5 or more	5.9

These findings indicated "that most items experience zero demand or one demand over the observation and a very few have large demands [Ref 12:12]."

Resupply Time

The base stockage model considered resupply time "as base repair cycle time, depot resupply cycle time or some combination of both [Ref 12:9]." Previous research

found that routine base repair cycle times averaged one week or less (Ref 12:9). Order and shipping time between the base and depot was assumed to have a mean of 6.74 days and standard deviation of 4.43 days (Ref 12:10). The resupply time for any base was (Ref 12:32):

$$T = [(PBR \cdot RCT) + (1-PBR)(OST)] \qquad \text{(Eq 26)}$$

Model Assumptions

The base stockage model made five key assumptions:

1. Demands followed a Poisson probability distribution, and were stationary about a mean.

2. Resupply times were stationary with a known mean and standard deviation.

3. All spares were fully repairable at the depot.

4. Parts did not wait for repairs, and no repairs were expedited.

5. The depot stock was always positive (Ref 12:31).

Model Formulation

The base stockage model computed the expected number of base backorders with (Eq 6):

$$E(B_i) = \sum_{r_i=s+1}^{\infty} (r_i - s_i)\, p(r_i \mid \lambda_i T_i) \qquad \text{(Eq 6)}$$

This formula is the sum of all possible backorders times their unique probability of occurrence. The resupply probabilities were determined by a Poisson distribution.

Using marginal analysis, the model maximized the inventory fill rate; or conversely, minimized the sum of expected backorders across all items:

$$\text{Min} \sum_{i=1}^{n} E(B_i) \qquad \text{(Eq 27)}$$

subject to the constraint (Ref 12:31-38):

$$\sum_{i=1}^{n} C_{pi} S_i \leq \$ \qquad \text{(Eq 28)}$$

METRIC

The Multi-Echelon Technique for Recoverable Item Control (METRIC) was designed to identify inventory stockage and distribution levels which "optimize system performance for specified levels of system investment [Ref 29:1]." METRIC was a two-echelon model were one depot served several bases (Ref 29:2). Designed for application to weapon systems, METRIC provided inventory managers a range of cost-effectiveness support alternatives (Ref 29:1). METRIC was a logical extension of the Base Stockage Model; also, the two models shared a common author.

METRIC had three main purposes. Its primary function was to find optimal stock levels at each echelon for

every stocked item subject to a system performance or investment constraint. Second, given fixed stock levels of an item, it found the most optimal allocation of stock between the depot and bases. Third, METRIC evaluated the system performance and investment cost for any allocation of stock between the depot and bases (Ref 29:2).

Model Assumptions

METRIC shared the five Base Stockage Model assumptions, and required five more:

1. Its primary objective was to minimize the total expected backorders for all recoverable items at each base supporting a specific weapon system (Ref 29:6).

2. The decision to return an asset to the depot for repair was a function of the type of failure, and the base's repair capability (Ref 29:10).

3. No lateral resupply between bases was allowed (Ref 29:6).

4. Depot repair action began immediately after an item arrived at the depot (Ref 29:11).

5. Demand data from several bases could be pooled for the initial estimate of demand (Ref 29:12).

Model Formulation

The average fraction of units that were repaired on-base was the probability that an item was base

repairable (PBR). The probability that an item was repaired at the depot was one minus PBR (Ref 29:12).

When the positive depot stock assumption was relaxed, backorder resupply time became a function of the depot stock level (Ref 29:14). If the number of units in depot repair was equal to, or less than, the depot authorized stock, then resupply time equalled OST (Ref 29:14). If the number of units in depot repair exceeded authorized depot stock, then resupply time included an average depot delay (D_{avg}) (Ref 29:14).

The total demand (λ_d) the depot experienced from all bases (m) for any item was (Ref 29:13):

$$\lambda_d = \sum_{j=1}^{m} \lambda_j \, (1-PBR_j) \qquad \text{(Eq 29)}$$

The expected number of depot backorders at any random time was (Ref 29:15):

$$E(B_d) = \sum_{r=s_d+1}^{\infty} (r-s_d)\, p(r \mid \lambda_d DRT) \qquad \text{(Eq 30)}$$

Here, DRT was the depot repair and retrograde time. Retrograde time was the period required to ship a failed asset from a base to the depot (Ref 29:3). The average depot delay per demand was (Ref 29:15):

$$D_{avg} = E(B_d)/\lambda_d \qquad \text{(Eq 31)}$$

The new repair cycle pipeline quantity was (Ref 29:14):

$$Q_p = \lambda T = D_d[(PBR)(RCT) + (1-PBR)(OST+D_{avg})] \qquad \text{(Eq 32)}$$

The expected backorders at any random time for any base was (Ref 29:14):

$$E(B_i) = \sum_{r=s+1}^{\infty} (r-s_i)p(r|\lambda T) \qquad \text{(Eq 6)}$$

The total depot and base stock, the total amount of stock in the system (S_t), was found with (Ref 10:25):

$$S_t = S_d + \sum_{j=1}^{m} S_j \qquad \text{(Eq 33)}$$

Marginal Analysis

METRIC used marginal analysis to find the allocation of stock between the depot and bases which minimized expected base backorders (Ref 29:16). Using either marginal analysis, or a Langrangian procedure, the set of stock for all bases was identified which satisfied the objective function (Ref 29:17):

$$\text{Min} \sum_{j=1}^{m} \sum_{i=1}^{n} E(B_{ij}) \qquad \text{(Eq 34)}$$

The solution set was subject to the budget constraint (Ref 29:16):

$$\sum_{j=1}^{m} \left(\sum_{i=1}^{n} S_{ij} + S_{di} \right) \cdot C_i \leq \$ \qquad \text{(Eq 35)}$$

Model Critique

METRIC had four serious weaknesses. First, it did not allow for lateral resupply. Second, end-item availability was not considered. Third, expendables were not considered. Finally, METRIC explicitly assumed OST was always routine and never expedited.

LMI Availability Model

The Logistic Management Institute's (LMI) Availability Model was designed to optimize spares stockage based upon weapon system availability (Ref 18:10-12). METRIC optimized spares stockage by minimizing expected base backorders (Ref 18:10). However, this policy did not ensure that the expected number of NMCS aircraft was minimized (Ref 18:10). The LMI Availability Model converted expected backorders into expected NMCS aircraft, and minimized the expected NMCS for any inventory investment (Ref 18:10-12). The model developed a "shopping list" for recommended spares investment based upon the contribution to expected NMCS reduction per dollar invested (Ref 18:14-15).

Model Assumptions

The LMI Availability Model required the ten METRIC assumptions plus four additional assumptions:

1. A no cannibalization policy was followed.

2. An aircraft was not available if it lacked any NMCS-causing spare.

3. The failure of any NMCS-causing component was independent of the aircraft's status, and of all other components.

4. When the quantity per aircraft of any spare exceeded one, the failure of any unit was independent of the failure of any similar unit (Ref 18:12).

Model Formulation

The probability an aircraft was available (PAA) was (Ref 18:45):

$$PAA = \prod_{i=1}^{n} \left(1 - \frac{E(B_i)}{N \cdot QPA_i}\right)^{QPA_i} \qquad \text{(Eq 15)}$$

The reduction in NMCS aircraft resulting from adding one unit of stock (s_i+1) was the NMCS improvement factor (NIF) (Ref 18:46):

$$NIF = \frac{P(i|s_i+1)}{P(i|s_i)} \qquad \text{(Eq 36)}$$

The new PAA was (Ref 18:46):

$$PAA_{(s+1)} = (NIF)(PAA_s) \qquad \text{(Eq 37)}$$

Model Optimization

The model could find the optimal stockage position by maximizing the aircraft availability subject to a budget constraint. However, this was not a mathematically separable function, so an equivalent objective function was (Ref 18:60):

$$\text{Max} \quad \Delta F = \frac{\log P(i|s_i+1) - \log P(i|s_i)}{C_{pi}} \qquad \text{(Eq 38)}$$

The new objective function was still subject to an inventory investment constraint.

Model Critique

The LMI Availability Model had three main limitations. First, the model did not consider expendable items. Second, cannibalization was not allowed. Finally, the model used only the routine resupply time, expediting was not considered.

The Cost Benefit of Stockage

Based on METRIC and METRIC-LMI, Demmy, et al., developed a base-level model that measured the cost-benefit of stocking low demand items. They proposed that the

recoverable model stocked "fast-moving" items at both the depot and base-level, while "slow-moving" items were only stocked at depot. Earlier studies demonstrated the low demand incongruity contributed to from 30 to 50 percent of all aircraft NMCS incidents. Demmy believed that inadequate stockage of low demand assets was the key NMCS-causing factor.

> The critical question is whether or not it is economically desirable to reduce this downtime by stocking low-demand items at the base. Specifically, is the value of potential increases in aircraft availability sufficient to justify additional base level inventories [Ref 9:2].

Model Formulation

The cost-benefit model defined low-demand items as those experiencing two or fewer base-level demands per year (Ref 9:10). The model required the basic METRIC and METRIC-LMI assumptions. It began with the METRIC-LMI probability that a random aircraft was available (Ref 9:5):

$$PAA = \prod_{i=1}^{n} \left(1 - \frac{E(B_i)}{N\ QPA_i}\right)^{QPA_i} \qquad \text{(Eq 15)}$$

The expected number of operational aircraft (ENOA) was (Ref 9:506):

$$ENOA = PAA \cdot N \qquad \text{(Eq 39)}$$

If all n items were ranked according to their annual demands, the expected number of operational aircraft

could be split into low demand ($i = 1$ to ℓ) and high demand ($i = \ell+1$ to n) portions (Ref 9:6):

$$\text{ENOA} = \left(\prod_{i=1}^{\ell} \left(1 - \frac{E(B_i)}{N\ QPA_i}\right)^{QPA_i} \right) \left(\prod_{i=\ell+1}^{n} \left(1 - \frac{E(B_i)}{N\ QPA_i}\right)^{QPA_i} \right) \cdot N \qquad \text{(Eq 40)}$$

Afterward, let Q^L and Q^H represent the low and high demand terms. The low demand component denoted "the probability that a low demand item is not causing a 'hole' in a randomly selected aircraft [Ref 9:6]."

If low demand items were never backordered, the expected number of operational aircraft would be (Ref 9:6):

$$N_0 = Q^H \cdot N \qquad \text{(Eq 41)}$$

When (Eq 40) and (Eq 41) were combined, the expected number of operational aircraft became (Ref 9:6):

$$\text{ENOA} = N_0 \cdot Q^L \qquad \text{(Eq 42)}$$

Considering only low demand items, the ENOA equation simplified to (Ref 9:7):

$$\text{ENOA} = N_0 \left[1 - \sum_{i=1}^{\ell} \frac{E(B_i | s_i)}{N} \right] \qquad \text{(Eq 43)}$$

After increasing the amount stocked by one, and simplifying, the change in ENOA was (Ref 9:9):

$$\Delta ENOA = Q^{H}[E(B_i|S_i) - E(B_i|S_i+1)$$

or

$$\Delta ENOA = Q^{H}(1-RR_i) \qquad \text{(Eq 44)}$$

When the amount stocked was zero, (Eq 44) became (Ref 9:10):

$$\Delta ENOA = Q^{H}(1-e^{-\lambda T}) \qquad \text{(Eq 45)}$$

Since:

$$e^{-\lambda T} = \sum_{d=0}^{\infty} \frac{(-\lambda T)^{d}}{d!} \qquad \text{(Eq 46)}$$

and quadratic and higher terms were irrelevant for low-demand items, the change in ENOA became (Ref 9:10):

$$ENOA = Q^{H}\lambda_i T_i \qquad \text{(Eq 47)}$$

Thus, (Eq 47) was the "average reduction in the number of NORSG [NMCS] aircraft due to addition of one spare for a low demand item [Ref 9:11]."

Model Analysis

Demmy expressed the benefit gained from one additional available aircraft as the aircraft's cost (C_{ac}) (Ref 9:12). The benefit (BENF) from stocking an item was (Ref 9:12):

$$BENF_i = \Delta ENOA_i \cdot C_{ac} \qquad \text{(Eq 48)}$$

The investment (INV) required to stock the item at all bases was (Ref 9:12):

$$INV_i = m \cdot C_{pi} \qquad \text{(Eq 49)}$$

Therefore, the cost-benefit (C/BENF) of stockage becomes (Ref 9:12):

$$C/BENF = \frac{INV_i}{BENF_i} \qquad \text{(Eq 50)}$$

Duke and Elmore's Study

First Lieutenants James Duke and Kenneth Elmore were members of the Air Force Institute of Technology class 81-S. Their thesis developed an alternative stockage algorithm for METRIC, based upon maximizing weapon system availability (WSA) (Ref 10:5-6). Their system of study, the Airborne Command and Control Capsule (ABCC), demonstrated unique characteristics which facilitated several modeling simplifications (Ref 10:38). Duke and Elmore's algorithm bridged the gap between minimizing system backorders (METRIC) and maximizing system availability.

Unique Characteristics

The uniqueness of the ABCC system allowed several simplifying assumptions. Since the ABCC was supported and operated from one base, it was most efficient to stock all spares at the base (Ref 10:37). The depot served only as a

higher level repair facility (Ref 10:37,45). All items were assigned equal essentiality, each a potential NMCS-causing item (Ref 20:1). Demands were stationary about λ and followed a Poisson distribution; resupply times were stationary about T. All items were repairable at either the base or depot, and no items were condemned (Ref 20:1). The ABCC was the sole user of the sample items, and no indenture relationships existed in the sample (Ref 20:2). A full cannibalization policy was followed (Ref 10:44).

Model Formulation

The algorithm was a combination of the METRIC and Average NMCS techniques. The simple Poisson formula represented the frequency of demands (Ref 20:3). Since the depot served only as a repair facility, the time associated with depot repair included the sum of OST, depot delay, and retrograde (RET) times (Ref 10:41):

$$T = [(PBR)(RCT) + (1-PBR)(OST+D+RET)] \qquad \text{(Eq 51)}$$

Retrograde was the amount of time necessary to ship the failed asset from the base to the depot, and was included in DRT by the METRIC model (Ref 29:3).

Weapon system availability was based upon the Average NMCS method. The probability of exactly one NMCS aircraft was (Ref 10:16):

$$P(1\ NMCS) = OR_{k=1} - OR_{k=0} \qquad \text{(Eq 11)}$$

The expected number of NMCS aircraft at any time was (Refs 10:16; 20:3):

$$E(NMCS) = \sum_{k=0}^{N} kp(k) \qquad \text{(Eq 12)}$$

Conversely, the weapon system availability was (Ref 20:5):

$$WSA = 1 - \frac{E(NMCS)}{N} \qquad \text{(Eq 52)}$$

A true optimum stockage policy would require maximizing availability; however, (Eq 52) was a nonseparable function (Ref 6:21). Therefore, the algorithm used a marginal analysis sorting technique, although it could not guarantee optimality.

> In this procedure, each incremental asset purchased was determined to be the asset which provided the greatest reduction in expected NORS [NMCS] aircraft per dollar spent [Ref 10:44]."

The total inventory investment was limited to the budgets that the Air Force recoverable model recommended (Ref 10:46).

Results

The cost-effective NMCS algorithm provided a slightly higher system availability than METRIC, under the budgeting constraint. The availability provided by both the algorithm and METRIC exceeded that provided by

the Air Force recoverable model. At increasing investment levels, the algorithm and METRIC system availabilities converged (Ref 10:57).

Related Studies

MOD-METRIC

MOD-METRIC was a multi-item, multi-echelon, multi-indenture inventory model (Ref 23:472). MOD-METRIC simulated one depot serving several bases; it considered two special types of recoverables, line replacement units (LRU) and shop replacement units (SRU) (Ref 23:472).

LRUs and SRUs share an indentured relationship. LRUs are typically high-cost recoverable assets that consist of recoverable subassemblies. LRUs may be removed from a system as a unit; for example, an engine or radar assembly (Ref 21:393). SRUs are the modular subassemblies of LRUs. SRUs are typically much lower in cost than LRUs (Ref 21:626).

The lack of an LRU will ground an aircraft. However, a missing SRU may ground an aircraft, or delay the repair of a spare LRU (Ref 23:475). The driving maintenance concept is to minimize the backorders of high-cost LRUs, and to fill the repair cycle pipeline with lower-cost SRUs (Ref 23:473).

The METRIC assumption that all items have an equal essentiality is inappropriate for modularly designed

systems (Ref 23:474). Under METRIC logic, an SRU backorder was as critical as an LRU backorder (Ref 23:475). Since METRIC minimized base-level backorders, it tended to buy more relatively cheap SRUs and fewer relatively expensive LRUs. This resulted in fewer base-level backorders of SRUs, and a lower availability of LRUs at base-level.

MOD-METRIC recognized the indenture relationship between LRUs and SRUs. It modified the METRIC resupply time for LRUs to include the average delay, experienced at base-level, due to SRUs (Ref 23:476). Through marginal analysis MOD-METRIC minimized the backorders of LRUs at base-level, subject to an investment constraint (Ref 23:477).

Dyna-METRIC

Steady state models, such as METRIC and MOD-METRIC, when applied to nonstationary processes provided inadequate estimates of inventory system performance (Ref 16:iii). Attempted adaptation of steady state models to dynamic environments have been unsuccessful (Ref 16:iii). Dyna-METRIC was designed for a dynamic environment; for example, the transition period between peacetime and wartime military operations.

Steady state inventory models adequately support Air Force peacetime operations (Ref 16:1). Dyna-METRIC provided a means "of transient performance measurement for alternative supply and maintenance strategies [Ref 16:iii]."

Demand behavior was especially important since demands may greatly accelerate at the initiation of hostilities and gradually drop due to aircraft attrition (Ref 16:1).

Dyna-METRIC answered two problems of recoverable spares management:

1. How much should be stocked?

2. What level of performance will the stock provide (Ref 16:2)?

Dyna-METRIC operated under the assumption of full cannibalization (Ref 16:9).

Summary

Current inventory models offered a variety of techniques to deal with specific management situations. Most models sought to optimize the effectiveness of inventory stockage through either minimizing backorders, or maximizing availability. However, inventory stockage was usually constrained by budget limits. Frequently, the models were designed to handle either expendables or recoverables, but not both. The models allowed for either a full or zero cannibalization policy, and often considered base repair capabilities. All reviewed models, either explicitly or implicitly, assumed that resupply was always routine and never expedited.

Unfortunately, current models only partially solve the problems of automatic test equipment (ATE). To

optimize inventory support for ATE, an alternative inventory heuristic is needed which:

1. Considers very low demand items.

2. Operates without cannibalization.

3. Considers both expendables and recoverables.

4. Incorporates both routine and expedited resupply.

5. Allows for a partial base repair capability.

6. Seeks to maximize system availability.

7. Ranks candidate items in the most cost-effective purchase sequence, and offers managers a variety of investment criteria.

Chapter III develops a heuristic which incorporated these attributes.

CHAPTER III

METHODOLOGY

Overview

A brief discussion of the F-15 AIS is presented first. Next, the candidate item selection process is outlined, followed by a description of how item parameters were developed. Afterwards, the algorithm development is shown in three major stages. The initial stage details the impact of expediting resupply upon expected backorders, and demonstrates the need for an alternative inventory technique. The second stage develops an alternative heuristic backorder estimate formula, and validates its operation. The final stage discusses model optimization, applying marginal analysis and deriving the implied inventory penalty cost.

System Background

The F-15 AIS system was selected for research; four considerations drove the selection process. First, the system was in its operational maturity, avoiding system start-up or phase-down disturbances. Second, the low density of AIS systems per base made simplifying assumptions reasonable. Third, Headquarters TAC maintained a

comprehensive AIS NMCS data base. Fourth, the AIS was representative of automatic test equipment in general.

The F-15 AIS was composed of six test stations; however, research was limited to the Displays Test Station (Figure 2) which "provides automatic testing capabilities for Intermediate Level maintenance of F/TF-15A LRUs [Ref 1:5-14]." The Displays Test Station had the largest number of F-15 AIS NMCS incidents in FY 1981. During this period, five TAC units operated and supported ten Displays Test Stations (Refs 2; 4; 13; 34; 35):

Base	Number of Test Stations
Eglin AFB, Florida	2
Holloman AFB, New Mexico	2
Langley AFB, Virginia	3
Luke AFB, Arizona	2
Nellis AFB, Nevada	1

Candidate Item Selection

Headquarters TAC/LGSW provided a selective review of the Mission Capability Analysis System (D-165) which listed all F-15 AIS NMCS incidents occurring in FY 1981. Two hundred and ninety incidents were attributed to the Diaplays Test Station.

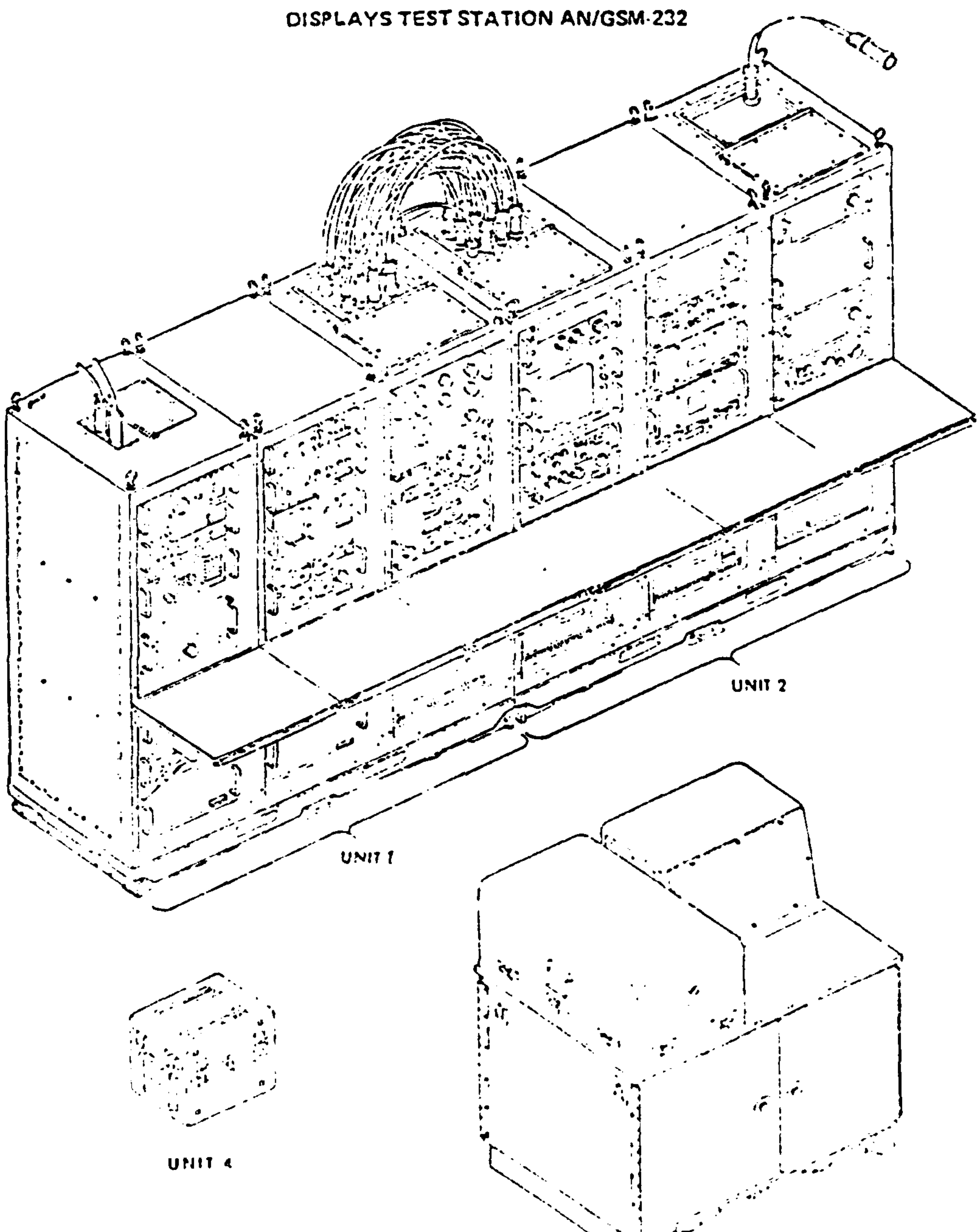

Fig. 2. Displays Test Station--F-15 AIS

Command-Level Screening

Four criteria were used to select candidate items at the command-level:

1. Only demands initiated and satisfied during FY 1981 were eligible. All selected NMCS incidents were closed and their duration known.

2. Only demands for items assigned a valid national stock number (NSN) were retained. Locally purchased or part-numbered items were eliminated since the consistency of their identification was suspect.

3. Only items available from Department of Defense (DOD) depots were considered. Therefore, all candidate items were equally available to the five test bases.

4. Only demands satisfied with material from DOD depots were considered. NMCS demands submitted in error, or satisfied through lateral resupply, were eliminated.

Base-Level Screening

One hundred and ninety-seven potential study items remained after the initial screening. Next, computerized supply system inquiries for the remaining items were requested from the five bases. The inquiries provided current asset demand, repair cycle, stock control, and item record data. Fifty eight additional items were eliminated after reviewing the inquiries. The items were removed for three reasons:

1. If an item's NSN was not currently loaded in the UNIVAC 1050-II computer at any base.

2. If an item's total demand data contained more than ten demands TAC-wide.

3. Items coded for disposal from the active Air Force inventory.

Item Parameterization

The algorithm required four parameters from every selected asset: (1) yearly demands, (2) the percent of base repair, (3) the repair cycle time, and (4) the order and shipping time. The base supply inquiries provided the raw data needed to develop the first three parameters.

Usage Rates

Gathering realistic base usage data for infrequently demanded items is difficult. Sherbrooke recommends pooling the item usage history from several bases to resolve this problem (Ref 29:12). This approach was used to develop the total demands for each selected asset.

The supply inquiries contained one year of base-level item demand history. The yearly demands were totaled and divided by the number of test stations. This procedure estimated the item's yearly demand resulting from supporting one test station at one base. For example, if ten test stations generated only two requests, the equivalent base demand would be one-fifth of a demand per

year. It should be noted that the Standard Base Supply System (SBSS) would not retain a usage rate that low, and that such an item would not be stocked under current procedures.

Percent of Base Repair

Infrequent repair transactions accompany low usage rates. The SBSS retains an item's repair history for one year, updating the history in quarterly increments. Since repair data older than one year are lost, low demand items frequently reflect no base repair capability, even when one exists.

Theoretically, each base supporting an identical system should have a similar repair capability. The total number of units repaired by the five bases, divided by the total number of units entering the bases' repair cycles, provided an item's estimated percent of base repair. This average extended to every base, even though the base may not have repaired the item within the previous twelve months.

Base Repair Time

The SBSS also records the time required for all successful repairs in the item's repair history. Due to the SBSS twelve-month limit, low-demand items can lose valid, but scarce, repair times. Again, pooling and

averaging the item's repair times provided the best base repair time estimate.

Order and Shipping Time

Geographically, each base and depot are separated by varying distances. The distance, in turn, directly affects the base's order and shipping time (OST), primarily through transportation network differences. Variations in OST affect item availability at each base.

The unique set of OST between each base and depot was collected from the base Routing Identifier Listing (Q05). The SBSS accumulates the actual time required for each requisition to be satisfied. Any times exceeding 175 percent of the DOD standard for the relevant requisition priority are deleted. The remaining times are pooled, averaged, and published quarterly in the base Q05. The published OST times are representative of the resupply duration for any item, whether frequently or infrequently demanded.

Table 1 lists the OST data by base for priority groups one (expedited) and three (routine) (Refs 7; 17; 19; 22; 26). The Q05 for Holloman AFB, New Mexico did not contain OST data from the Navy depot. Consequently, the times from its closest neighbor, Luke AFB, Arizona were substituted.

TABLE 1

ORDER AND SHIPPING TIMES

Source of Supply	Eglin		Holloman		Langley		Luke		Nellis	
	PG1	PG3	PG1	PG3	PG1	PG3	PG1	PG3	PG1	PG3
Sacramento Air Logistics Center, CA	8	22	7	16	9	22	7	18	8	25
Ogden Air Logistics Center, UT	7	20	7	21	8	21	7	17	8	26
McClellan Air Logistics Center, CA	7	18	7	17	7	21	7	20	7	29
San Antonio Air Logistics Center, TX	7	21	6	15	8	27	7	16	8	32
Defense Construction Supply Center, OH	7	21	7	21	7	26	6	19	6	28
Defense Electronics Supply Center, OH	7	20	7	21	8	19	6	20	7	29
Defense Industrial Supply Center, PA	7	22	8	21	7	24	6	20	7	29
Defense General Supply Center, VA	7	21	7	21	7	20	7	18	8	33
Navy Materiel Control Center, PA	8	22	9	21	7	20	9	21	9	26

Note: Order and shipping time (days); Priority (PG1) and Routine (PG3).

Data Description

Table 2 lists the 139 items that satisfied the screening criteria. The column headings are:

1. National Stock Number (NSN)--the unique numeric designator identifying a specific inventory item.

2. Total Demands (TDMD)--the sum of annual demands for each NSN from all five bases. TDMD included both routine and expedited requirements. Demands for interchangeable and substitute NSNs were combined under the master (preferred) NSN.

3. NMCS Demands (NDMD)--the total NMCS incidents charged against each NSN during FY 1981.

4. Source of Supply (SOS)--the DOD depot responsible for managing each item, identified by a unique alphanumeric Routing Identifier Code (RIC).

RIC	Depot
FFZ	Sacramento Air Logistics Center, California
FGZ	Ogden Air Logistics Center, Utah
FPZ	San Antonio Air Logistics Center, Texas
S9C	Defense Construction Supply Center, Ohio
S9E	Defense Electronic Supply Center, Ohio
S9G	Defense General Supply Center, Virginia
S9I	Defense Industrial Supply Center, Pennsylvania
N35	Navy Materiel Control Center, Pennsylvania

TABLE 2

SELECTED ASSETS

NATIONAL STOCK NUMBER	TDMB	NDMB	SOS	ERRC	PBR	RCT	UNIT PRICE ($)	NOMENCLATURE
2910 00 110 9692	02	01	5	EX			17.90	NOZZL ASY FUE
2910 00 780 0934	01	01	5	EX			33.94	HOLDER ASY PUM
3120 01 090 5601	01	01	7	EX			18.49	BUSHING SLV
4140 00 525 3197	00	01	4	EX			381.72	FAN,VANEAXIAL
4140 00 525 9214	02	02	8	EX			98.84	FAN,TUBEAXIAL
4310 01 030 4239	01	01	5	EX			6.96	FILTER ELEMENT
4720 00 309 2652	02	01	5	EX			6.94	HOSE PREFORMED
4920 00 295 1152	06	02	4	RC	.14	4.0	8299.00	CIRCUIT CARD ASY
4920 00 339 3632	06	01	4	RC	.83	8.4	1923.04	SAMPLING HEAD
4920 00 348 5883	01	02	4	EX			1060.38	CIRCUIT CARD ASY
4920 00 352 2798	07	02	4	RC	.14	11.0	1822.00	CIRCUIT CARD ASY
4920 00 427 8009	05	02	4	RC	.20	5.0	5557.83	ELECTRONIC COMPON
4920 00 516 6854	01	01	4	EX			588.29	CIRCUIT CARD ASY
4920 00 530 1473	03	01	4	EX			45.76	CONNECTOR & HOLDER
4920 00 563 9146	03	01	4	EX			5770.12	ELECTRONIC COMPON
4920 01 004 2373	08	01	4	RC	.00	0.0	873.00	CIRCUIT CARD ASY
4920 01 004 8568	00	01	4	RC	.00	0.0	1501.00	CIRCUIT CARD ASY
4920 01 005 3843	00	01	4	RC	.00	0.0	3402.00	ELECTRON COMPONE
4920 01 018 9092	03	01	4	EX			2245.20	CIRCUIT CARD ASY
4920 01 020 1635	01	01	4	EX			1346.32	CIRCUIT CARD ASY
4920 01 021 9537	05	01	4	RC	.00	0.0	2082.00	CIRCUIT CARD ASY
4920 01 035 3333	08	02	4	EX			849.75	CIRCUIT CARD ASY
4920 01 050 2457	03	01	4	EX			7161.78	CIRCUIT CARD ASY
4920 01 050 6356	01	03	4	RC	.00	0.0	2575.00	CIRCUIT CARD ASY
4920 01 051 6583	09	01	4	RC	.00	0.0	4052.00	CIRCUIT CARD ASY
4920 01 057 1154	01	01	4	EX			1632.33	CIRCUIT CARD ASY
4920 01 057 1192	01	02	4	RC	.00	0.0	37135.00	POWER SUPPLY ASY
4920 01 057 1642	01	02	4	EX			1273.03	DELAY LINE
4920 01 063 0162	00	01	4	EX			997.70	CIRCUIT CARD ASY
4920 01 063 0429	00	01	4	EX			1920.56	CIRCUIT CARD ASY
4920 01 063 1155	04	01	4	RC	.00	0.0	3069.00	CIRCUIT CARD ASY
4920 01 063 3615	02	01	4	EX			1598.19	CIRCUIT CARD ASY
4920 01 064 6199	04	02	4	RC	.33	1.5	4600.00	POWER SUPPLY
4920 01 066 0347	01	03	4	RC	.00	0.0	2375.00	CIRCUIT CARD ASY
4920 01 069 6638	00	01	4	EX			1724.13	CIRCUIT CARD ASY
4920 01 070 0832	00	01	4	EX			1953.87	CIRCUIT CARD ASY
4920 01 071 2780	00	01	4	EX			1506.80	CIRCUIT CARD ASY
4920 01 083 8366	02	03	4	RC	.17	1.0	3049.00	POWER SUPPLY
4920 01 084 6167	00	01	4	EX			1049.86	CIRCUIT CARD ASY
4920 01 085 4209	00	01	4	RC	.00	0.0	1572.00	CIRCUIT CARD ASY

TABLE 2--Continued

4920	01	085	7658	07	02	4	RC	.00	0.0	1579.00	CIRCUIT CARD ASY
4920	01	086	0487	02	02	4	RC	.00	0.0	87213.19	ANALYZER,TEST
4920	01	086	3753	03	02	4	RC	.00	0.0	1929.00	CIRCUIT CARD ASY
4920	01	086	5301	01	02	4	EX			1252.70	CIRCUIT CARD ASY
4920	01	090	5085	04	01	4	RC	.75	9.7	3972.00	CIRCUIT CARD ASY
4920	01	092	5802	07	01	4	RC	.20	6.0	2514.00	CIRCUIT CARD ASY
4920	01	095	8170	03	02	4	EX			3491.73	CIRCUIT CARD ASY
4935	01	030	5979	09	01	9	EX			24.50	CONNECTOR
5310	00	224	0748	07	01	7	EX			.01	WASHER,LOCK
5310	00	894	3637	06	01	7	EX			.48	NUT,SELF LOCKING
5315	01	107	2359	02	01	4	EX			19.61	PIN,SHOULDER,HEAD
5330	00	402	0204	05	01	7	EX			89.05	GASKET SET
5360	00	467	0351	06	01	7	EX			17.61	SPRING,HELICAL,COMP
5905	00	314	3327	01	01	6	EX			2.59	RESISTOR,FIXED,WIRE
5905	00	404	8777	01	01	6	EX			2.43	RESISTOR FIXED,WIRE
5905	00	471	4426	01	01	6	EX			2.73	RESISTOR,FIXED,WIRE
5910	00	230	7650	00	01	6	EX			3.92	CAPACITOR,FIXED
5925	00	103	5097	01	01	6	EX			39.67	CIRCUIT BREAKER
5925	00	179	1202	02	01	6	EX			46.07	CIRCUIT BREAKER
5925	00	198	4131	01	03	6	EX			46.96	CIRCUIT BREAKER
5925	01	037	6875	01	01	6	EX			51.81	CIRCUIT BREAKER
5925	01	038	1357	01	01	6	EX			67.46	CIRCUIT BREAKER
5925	01	038	4066	00	01	6	EX			51.81	CIRCUIT BREAKER
5925	01	044	0307	00	01	6	EX			63.54	CIRCUIT BREAKER
5930	00	457	7273	03	01	6	EX			9.97	SWITCH,TOGGLE
5930	00	728	0562	03	01	6	EX			41.35	SWITCH,SENSITIVE
5935	00	063	9010	01	01	6	EX			7.10	CONNECTOR PLUG,ELEC
5935	00	115	8549	01	01	6	EX			19.39	CONNECTOR,RECEPTACL
5935	00	146	4267	01	02	6	RC	.00	0.0	208.23	CONNECTOR BODY,PLUG
5935	00	167	7732	02	03	6	EX			.31	BUSHING ELECTRICAL
5935	00	194	1722	09	03	6	EX			29.45	CONNECTOR RECEPTACL
5935	00	328	2054	02	01	6	RC	.50	2.0	147.62	CONNECTOR BODY,RECE
5935	00	365	5623	05	01	6	EX			24.15	CONNECTOR PLUG ELEC
5935	00	374	7820	02	01	6	EX			96.78	CONNECTOR,RECEPTACL
5935	00	378	0941	06	01	6	EX			60.61	CONNECTOR BODY,ELEC
5935	00	430	4102	07	02	6	EX			32.58	CONNECTOR PLUG,ELEC
5935	00	434	2962	06	01	6	RC	.00	0.0	27.08	CONNECTOR BODY,RECE
5935	00	501	1921	02	01	6	EX			30.88	CONNECTOR PLUG,ELEC
5935	00	502	4828	01	01	6	EX			66.48	CONNECTOR RECEPTACL
5935	00	515	3587	02	01	6	RC	.00	0.0	139.80	CONNECTOR BODY,RECE
5935	00	525	5847	04	01	6	EX			32.75	CONNECTOR RECEPTACL
5935	00	529	0232	02	01	6	EX			17.22	CONNECTOR BODY,RECE
5935	00	534	7377	00	01	6	EX			41.94	CONNECTOR,PLUG,ELEC
5935	00	543	1713	06	01	6	EX			36.51	CONNECTOR,PLUG,ELEC
5935	00	577	0011	05	01	6	EX			2.13	CONNECTOR RECEPTACL
5935	00	593	9592	07	01	6	EX			20.04	CONNECTOR PLUG,ELEC
5935	00	715	2756	06	01	6	EX			11.54	CONNECTOR,PLUG,ELEC
5935	01	007	0527	04	01	1	EX			28.95	CONNECTOR,RECEPTACL
5935	01	007	5788	05	01	6	EX			80.16	ADAPTER,CABLE CLAMP
5935	01	013	4453	05	01	6	EX			2.71	CONNECTOR PLUG,ELEC

TABLE 2--Continued

5935	01	014	0396	01	01	6	EX			71.37	ADAPTER,CABLE CLAMP
5935	01	027	6464	05	02	6	EX			8.16	CONNECTOR PLUG,ELEC
5935	01	037	8220	05	02	6	EX			19.61	CONNECTOR RECEPTACL
5935	01	038	6492	00	01	6	EX			31.87	CONNECTOR,RECEPTACL
5935	01	046	9754	06	01	1	EX			66.26	CONNECTOR RECEPTACL
5935	01	048	0076	05	01	1	EX			17.60	CONNECTOR PLUG,ELEC
5935	01	049	2241	02	01	1	EX			33.40	CONNECTOR PLUG,ELEC
5935	01	051	1822	01	01	1	EX			21.84	CONNECTOR,RECEPTACL
5935	01	057	4481	01	01	6	EX			24.24	CONNECTOR,PLUG,ELEC
5935	01	057	5009	01	01	1	EX			12.08	CONNECTOR RECEPTACL
5935	01	086	7550	02	01	6	EX			28.06	ADAPTER,CABLE CLAMP
5940	00	579	4981	00	02	8	EX			7.79	TERMINAL,MALE PLUG
5940	00	581	7273	06	01	8	EX			1.25	FERRULE,METALLIC SH
5945	00	404	8608	02	02	6	EX			12.28	RELAY,ELECTROMAGNET
5945	01	021	1277	03	01	6	EX			306.97	RELAY,HYBRID
5945	01	027	3893	00	01	6	EX			5.88	RELAY,ELECTROMAGNETIC
5960	01	026	4666	00	01	6	EX			8775.00	ELECTRON TUBE
5961	00	026	8889	02	01	6	EX			.31	SEMI-CONDUCTOR DEVIC
5962	00	503	8035	01	01	6	EX			1.12	MICROCIRCUIT,DIGITA
5962	00	559	9775	02	02	1	EX			4.33	MICROCIRCUIT,DIGITA
5970	01	009	7664	02	01	8	EX			.27	INSULATION SLEEVING
5999	00	062	5218	01	01	6	EX			.34	CONTACT,ELECTRICAL
5999	00	080	9726	10	02	6	EX			2.84	CONTACT,ELECTRICAL
5999	00	551	0835	00	01	6	EX			15.54	CONTACT,ELECTRICAL
5999	00	766	9566	00	04	2	EX			2.62	CONTACT,ELECTRICAL
5999	00	824	5052	09	02	6	EX			4.30	CONTACT,ELECTRICAL
5999	00	902	3652	04	02	6	EX			.40	CONTACT,ELECTRICAL
5999	01	006	2495	04	01	6	EX			.74	CONTACT,ELECTRICAL
5999	01	048	3708	00	01	6	EX			.74	CONTACT,ELECTRICAL
6130	00	249	2772	00	01	1	RC	.00	0.0	384.00	POWER SUPPLY
6130	00	361	7110	01	01	1	RC	.00	0.0	666.90	POWER SUPPLY
6130	00	365	4532	00	02	1	RC	.00	0.0	2475.00	POWER SUPPLY
6130	00	369	6617	00	02	1	RC	.00	0.0	11568.00	POWER SUPPLY
6130	01	017	3598	06	01	1	RC	.17	14.0	1481.00	POWER SUPPLY
6130	01	018	5990	04	01	8	EX			600.87	POWER SUPPLY
6130	01	033	9491	01	01	1	RC	.00	0.0	7577.00	POWER SUPPLY
6210	00	337	4034	01	01	4	EX			9.07	LENS,SWITCH ACTVATI
6210	00	343	7076	01	01	4	EX			10.21	LENS,SWITCH ACTVATI
6210	00	385	9049	02	01	4	EX			11.85	LENS,SWITCH ACTVATI
6625	00	349	3575	01	01	4	RC	.00	0.0	5536.01	CIRCUIT CARD ASY
6625	00	359	1281	02	01	4	RC	.00	0.0	1237.19	LEAD,TEST
6625	00	498	4836	08	02	6	EX			75.28	DELAY LINE
6625	01	017	4569	03	01	4	RC	.00	0.0	297.79	CIRCUIT CARD ASY
6625	01	044	3467	00	02	4	RC	.00	0.0	3300.00	CIRCUIT CARD ASY
6625	01	045	4002	02	01	4	RC	.00	0.0	1512.00	CIRCUIT CARD ASY
6625	01	055	6532	01	01	4	EX			295.03	COMPONENT,BOARD ASY
6625	01	060	1888	08	02	4	RC	.22	2.5	1290.00	CIRCUIT CARD ASY
6625	01	066	8995	04	01	4	RC	.00	0.0	1574.00	CIRCUIT CARD ASY
9510	00	293	4962	00	01	7	EX			2.20	METAL BAR

5. Expendability, Recoverability, Repairability, Cost-Designator (ERRC)--identified the repairability of each item, expendable (EX) and recoverable (RC).

6. Percent of Base Repair (PBR)--the average percent of recoverable items repaired on-base; the PBR for expendable items was blank.

7. Repair Cycle Time (RCT)--the average time required to repair an item at base-level; the RCT for expendable items was blank.

8. Unit Price--the standardized item cost.

9. Nomenclature--the standardized item description.

Descriptive Statistics

The demand and depot frequencies were analyzed using the Statistical Package for Social Sciences. Figure 3 represents demands. Forty-four percent of the items were demanded once, and 17 percent twice. The average item in the set was demanded 2.9 times.

Figure 4 depicts the depot frequency. The Defense Electronic Supply Center (S9E) had the largest number of demands with 56, or 40 percent of the total. San Antonio Air Logistics Center (FPZ) had the second largest number of demands with 53, or 38 percent. The median unit price was $63.54, with a range from $0.01 to $87,213.

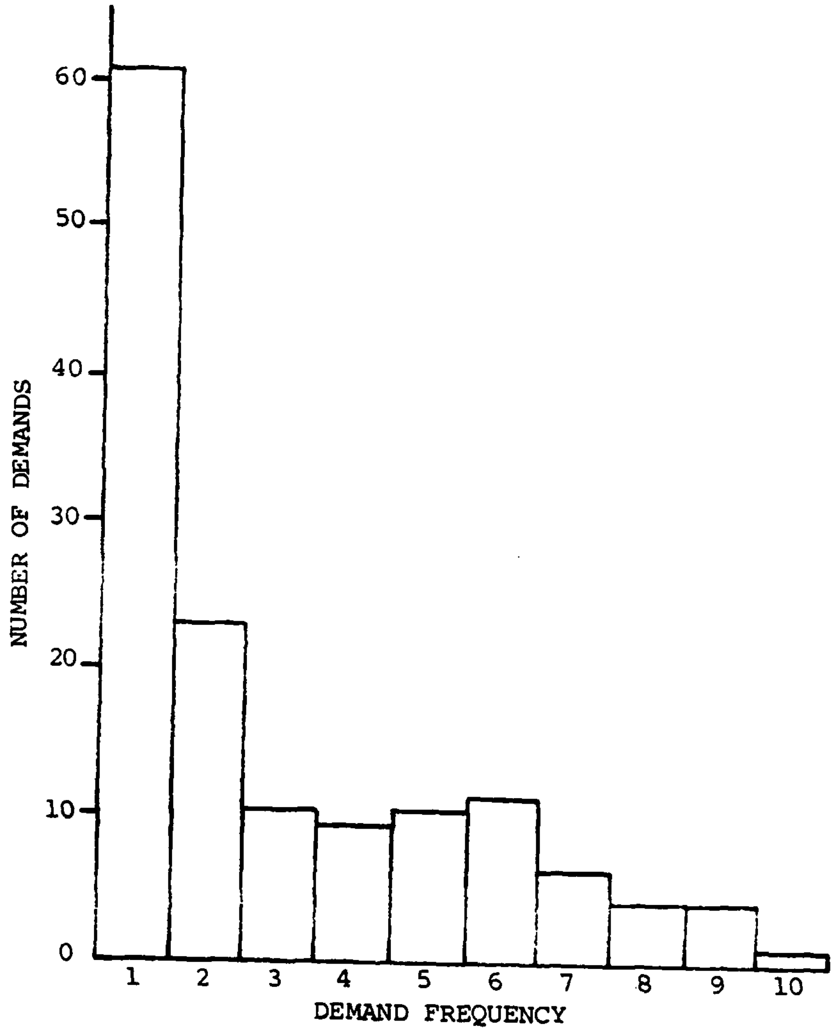

Fig. 3. Demand Frequencies

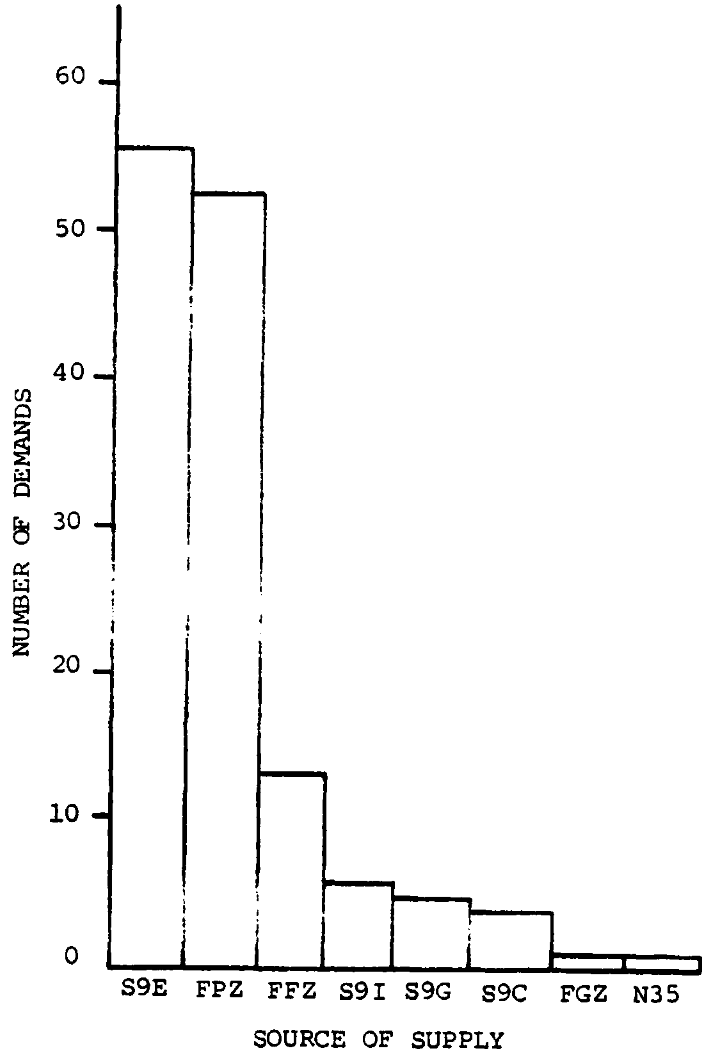

Fig. 4. Depot Frequencies

Algorithm Development

The algorithm was designed for systems having three characteristics:

1. Only one end-item was supported at each base, and the end-item had no built-in redundancy.

2. All items were equally essential and mission critical; each item had a quantity per application of one.

3. Item demands were independent and Poisson distributed about a mean, and each item's usage rate at a given location was one per year or less.

The algorithm produces a sequential listing of efficient inventcry investments based upon their incremental enhancement of system availability. The algorithm output allows the system manager to base inventory investment decisions upon: (1) budget limitations, (2) desired system availability, or (3) an implied penalty cost of stockage. The algorithm is explained in three sections: (1) the impact of expediting, (2) an heuristic backorder estimate formula, and (3) model optimization. Each section explains a portion of the algorithm, and compares it to current inventory theory or practice.

Expediting Resupply

Palm's Theorem assumes that the resupply time, or the time spent in resupply, was stationary about a single mean (Ref 8:8). However, the SBSS in fact operates

using two resupply priorities, with two corresponding resupply times.

The lowest priority, routine, is used when the level of stock on-hand is less than authorized stock, and there are no outstanding customer demands. The highest priority, expedite, is used when there is a customer demand and no available stock. The expedited resupply time is typically much shorter than the routine resupply time.

When an item is not authorized stock, all customer demands are backordered with a mean expedited resupply time T_X. When an item is authorized one stock unit, a first demand reduces stock to zero, and a routine stock replenishment occurs. A second demand, occurring during the routine resupply time (T_R) creates a backorder and an expedited resupply.

A simulation based upon A. Alan B. Pritsker's Q-GERT was designed to duplicate the SBSS operation, considering both routine and expedited resupply. The simulation incorporated some typical characteristics of low-demand items:

1. There was no base repair capability, all failures resulted in a demand on the depot.

2. The item was authorized one unit of base stock; the depot always had stock on-hand.

3. The number of demands was Poisson distributed and varied between one and five demands per year. The

mean routine OST was thirty days, the mean expedited OST was ten days.

Appendix A lists the simulation's programming.

Equation 6 represents the expected number of backorders (theoretical) according to Palm's Theorem assuming a single priority. Table 3 compares the simulation results with the theoretical expected backorders. Figure 5 shows the divergence of the theoretical and simulation values.

TABLE 3

A COMPARISON OF THEORETICAL AND SIMULATION EXPECTED BACKORDER VALUES

	EXPECTED BACKORDERS			
	Palm's Theorem		Simulation	
Demand Frequency	Expedited (T_X=10)	Routine (T_R=30)	Mean	Standard Deviation
1 Per Year	.00037	.00329	.0019	.0001
2 Per Year	.00147	.01280	.0066	.0002
3 Per Year	.00329	.02805	.0139	.0003
4 Per Year	.00579	.04858	.0235	.0005
5 Per Year	.00896	.07690	.0347	.0007

The Theoretical values for routine resupply (T_R=30) consistently overestimated the simulation's expected number of backorders. Always expediting resupply (T_X=10) caused the theoretical values to consistently underestimate the simulation's expected number of

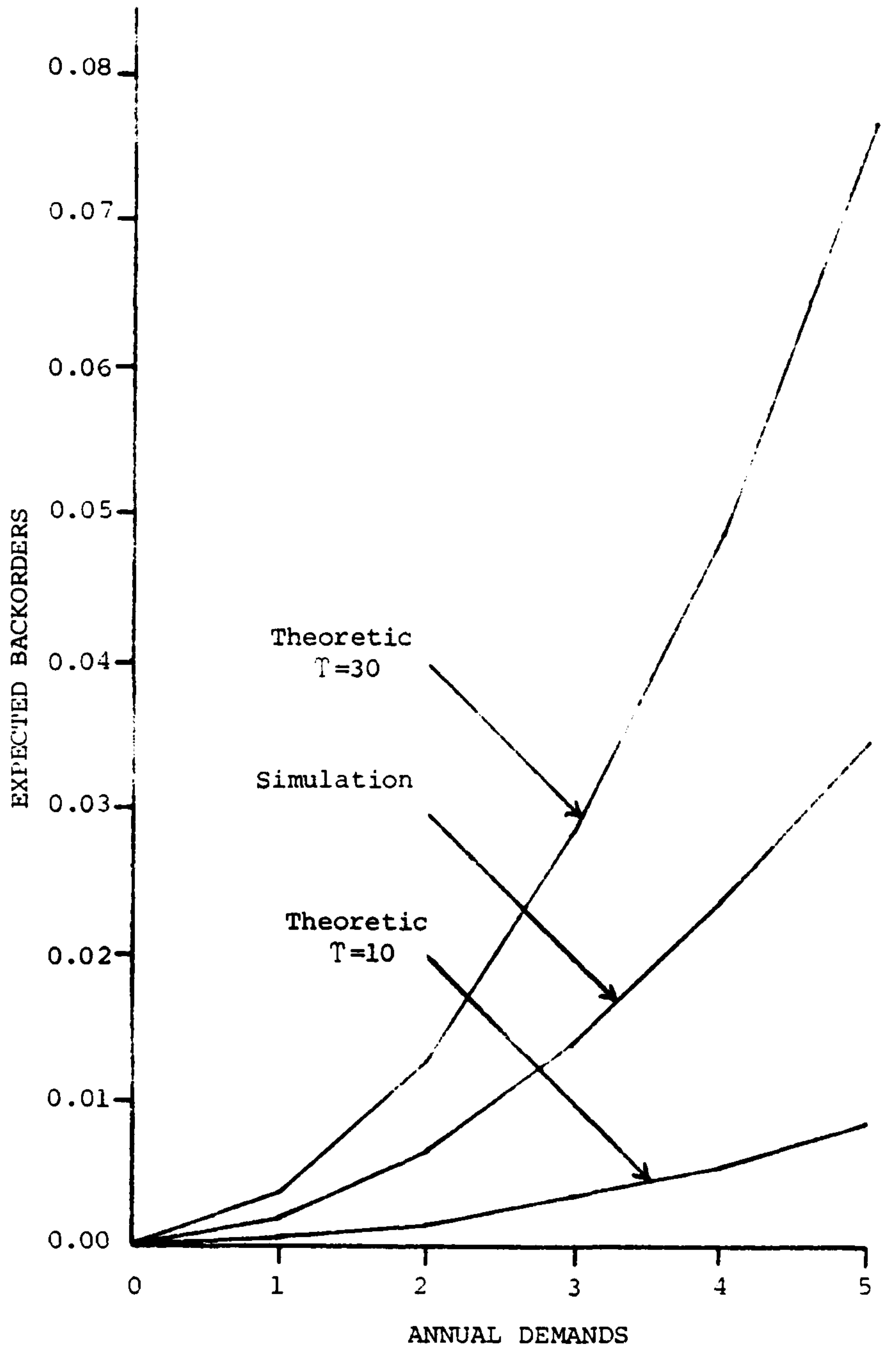

Fig. 5. The Divergence of Theoretical and Simulation Expected Backorder Values

backorders. These conclusions were strongly supported by hypothesis testing at the 95 percent confidence level. The disparity between the theoretical and simulation values indicate that a procedure is needed that more accurately computes the expected number of backorders for low usage items which enjoy expedited resupply for back-ordered demands.

Heuristic Backorder Estimation

When one unit is stocked, and the item has a zero percent of base repair, a backorder results only when a second demand occurs during routine resupply time. If λ was small enough that the probability of more than one demand during a routine resupply time was negligible, then the expected number of backorders could be approximated as:

$$E(B) = \left(\frac{\text{Exposures}}{\text{Year}}\right) \cdot p(\text{demand during } T_R) \cdot (\text{duration of resupply}) \qquad \text{(Eq 53)}$$

$$= \lambda \cdot \left(\sum_{r=0}^{\infty} p(r) - p(\phi)\right) \cdot T_E$$

$$= \lambda \cdot (1-e^{-\lambda T_R}) \cdot T_E \qquad \text{(Eq 54)}$$

where T_E was the effective resupply time.

The effective resupply time was a combination of T_X and T_R. Figure 6 diagrams the effective resupply

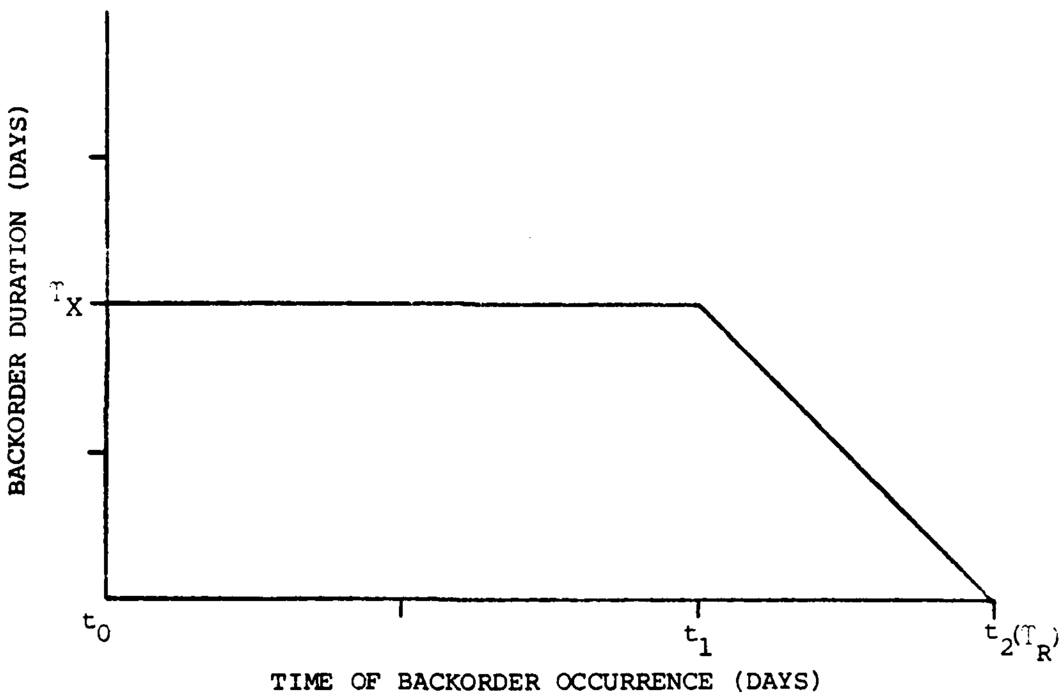

Fig. 6. Effective Resupply Duration

duration when T_X equalled ten and T_R equalled thirty days. From t_0 to t_1, the duration of all backorders is T_X. From t_1 to t_2, the backorder duration diminishes from T_X to zero. After t_1, the earlier routine stock replenishment arrives prior to the expedited resupply. When the expedited resupply does arrive, the backorder has been satisfied, and the new asset is added to stock.

If T_R and T_X were deterministic, the mean effective resupply time was the area under the curve:

$$T_{ED} = \frac{T_X(T_R - \frac{1}{2}T_X)}{T_R} \qquad \text{(Eq 55)}$$

In the deterministic case, the associated variance was zero. When T_X and T_R were independent, exponentially distributed random variables, the effective resupply duration became the new random variable (Ref 5:80-81):

$$T_{EE} = \frac{1}{\frac{1}{T_R} + \frac{1}{T_X}} \qquad \text{(Eq 56)}$$

In the exponential case, the variance is the square of the mean. This provided a reasonable upper boundary upon variance to contrast with the deterministic case. The heuristic averaged T_{ED} and T_{EE}, the minimum and "maximum" variance cases, to estimate T_E.

Table 4 compares the heuristic (Eq 56) and the Q-GERT SBSS simulation results. The effective resupply

TABLE 4

A COMPARISON OF THE HEURISTIC AND SIMULATION EXPECTED BACKORDER VALUES

	EXPECTED BACKORDERS		
		Simulation	
Expected Frequency	Heuristic	Mean	Standard Deviation
1 Per Year	.00171	.0019	.0001
2 Per Year	.00658	.0066	.0002
3 Per Year	.01422	.0139	.0003
4 Per Year	.02431	.0235	.0005
5 Per Year	.03655	.0347	.0007

time value was 7.917 days. Only the heuristic value at five demands per year was statistically different from the simulation result at the 95 percent confidence level. The remaining values were accepted as statistically equivalent. Five demands per year at one base, supporting one test station, would be equivalent to fifty demands per year in the data set. Usage rates that high were outside the research range of interest.

When one unit was stocked, and every failure was fully base reparable, (Eq 6) simplified to:

$$E(B) = \sum_{r=1}^{\infty} (r-1)p(r)$$

$$= \sum_{r=1}^{\infty} (r)p(r) - \sum_{r=1}^{\infty} (1)p(r)$$

$$= \sum_{r=0}^{\infty} (r)p(r) - [\sum_{r=0}^{\infty} p(r) - p(0)]$$

$$= \lambda T_{RCT} - 1 + e^{-\lambda T_{RCT}} \qquad \text{(Eq 57)}$$

where T_{RCT} was the mean base repair cycle time. Effectively, this equation was the sum of system backorders minus the reduction in backorders resulting from stocking one unit. Since every failure was base reparable, T_{RCT} represented the average resupply time according to Palm's Theorem.

The complete heuristic backorder estimate formula became a weighted average of (Eq 56) and (Eq 57). Equation 57 presented the expected number of backorders due to base repair, and was weighted by the item's percent of base repair. Equation 56 was the expected backorders resulting from depot resupply; accordingly, it was weighted by one minus the item's percent of base repair. The complete heuristic backorder estimate became:

$$E(B) = (PBR)\left[(\lambda)(T_{RCT}) - 1 + e^{-\lambda T_{RCT}}\right]$$

$$+ (1-PBR)\left[(\lambda)(1 - e^{-\lambda T_R})(T_E)\right] \qquad \text{(Eq 58)}$$

The Q-GERT simulation was modified to account for a variable percent of base repair, and compared to (Eq 58). The usage rates varied from one demand per year to one demand in four years. No item with usage rates that low would be stocked under current SBSS procedures. Since the actual base order and shipping times were used, the simulations T_X and T_R values were changed to match DOD resupply time standards, eight and thirty-one days respectively (Ref 32:6-22n).

The simulation and theoretical results are shown in Table 5; Appendix B contains the modified simulation programming. Since forty-one of the simulation values had a zero standard deviation, no conclusive statistical similarity tests were possible. The Base Stockage Model, (Eq 6) and (Eq 26), was used to develop comparison expected backorder values for the two extreme usage rates (Table 6). As Figures 7 and 8 demonstrate, the heuristic formula appears to be a much better predictor of expected backorders than the Base Stockage Model, which ignores priority resupply. Due to the internal roundoff programming of Q-GERT, the expected backorder values in Figure 7 appear to drop off more abruptly than is actually the case.

TABLE 5

A COMPARISON OF THE HEURISTIC AND SIMULATION EXPECTED BACKORDER VALUES BY PROBABILITY OF BASE REPAIR

Probability of Base Repair	USAGE RATES: 1 Per Year			1 Per 2 Years			1 Per 3 Years			1 Per 4 Years		
	Heuristic (Theoretic)	Simulation Mean	Simulation Std.	Heuristic (Theoretic)	Simulation Mean	Simulation Std.	Heuristic (Theoretic)	Simulation Mean	Simulation Std.	Heuristic (Theoretic)	Simulation Mean	Simulation Std.
0.0	.00149	.0017	.0001	.00038	.0004	.0000	.00017	.0002	.0000	.00010	.0001	.0000
0.1	.00135	.0014	.0001	.00034	.0004	.0000	.00015	.0002	.0000	.00009	.0001	.0000
0.2	.00121	.0012	.0001	.00031	.0003	.0000	.00014	.0002	.0000	.00008	.0001	.0000
0.3	.00107	.0010	.0000	.00027	.0003	.0000	.00012	.0001	.0000	.00007	.0001	.0000
0.4	.00093	.0008	.0000	.00024	.0002	.0000	.00010	.0001	.0000	.00006	.0001	.0000
0.5	.00079	.0006	.0000	.00020	.0002	.0000	.00009	.0001	.0000	.00005	.0000	.0000
0.6	.00065	.0005	.0000	.00017	.0001	.0000	.00007	.0001	.0000	.00004	.0000	.0000
0.7	.00051	.0005	.0000	.00013	.0001	.0000	.00006	.0000	.0000	.00003	.0000	.0000
0.8	.00037	.0003	.0000	.00009	.0001	.0000	.00004	.0000	.0000	.00002	.0000	.0000
0.9	.00023	.0002	.0000	.00006	.0000	.0000	.00003	.0000	.0000	.00001	.0000	.0000
1.0	.00009	.0001	.0000	.00002	.0000	.0000	.00001	.0000	.0000	.00001	.0000	.0000

TABLE 6

EXPECTED BACKORDERS AS PREDICTED BY THE BASE STOCKAGE MODEL

Probability of Base Repair	USAGE RATES 1 Per Year	USAGE RATES 1 Per 4 Years
0.0	.00351	.00022
0.1	.00295	.00019
0.2	.00244	.00016
0.3	.00198	.00013
0.4	.00156	.00010
0.5	.00120	.00008
0.6	.00090	.00006
0.7	.00062	.00004
0.8	.00039	.00002
0.9	.00022	.00001
1.0	.00009	.00001

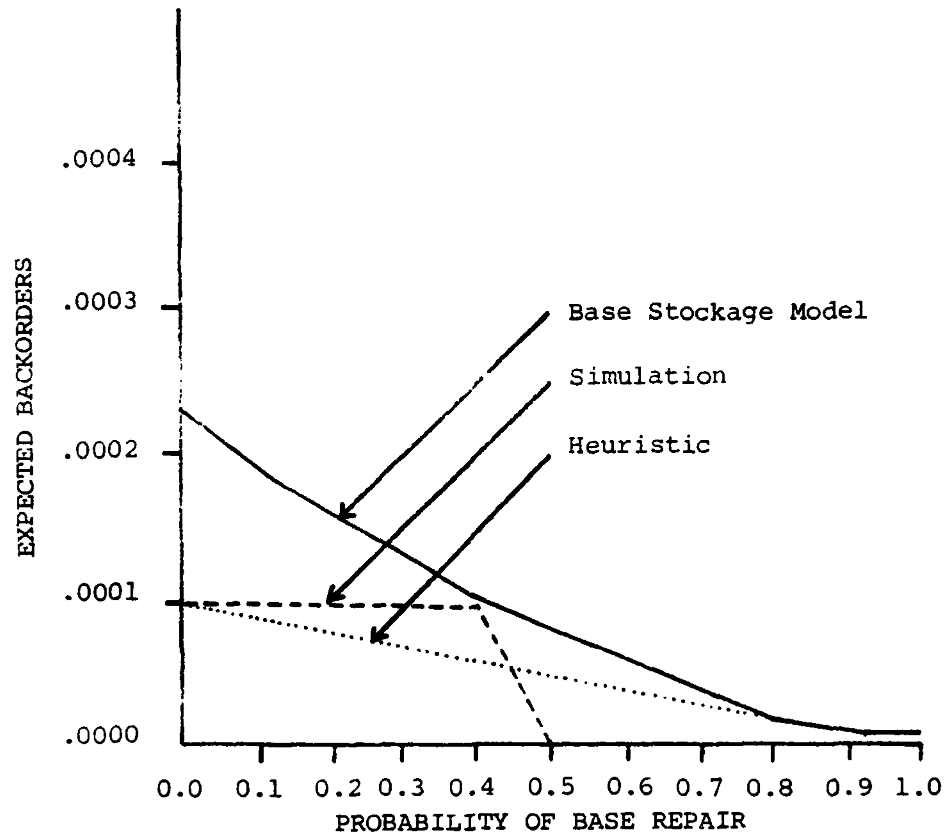

Fig. 7. A Comparison of Expected Backorders when Demand is One Every Four Years

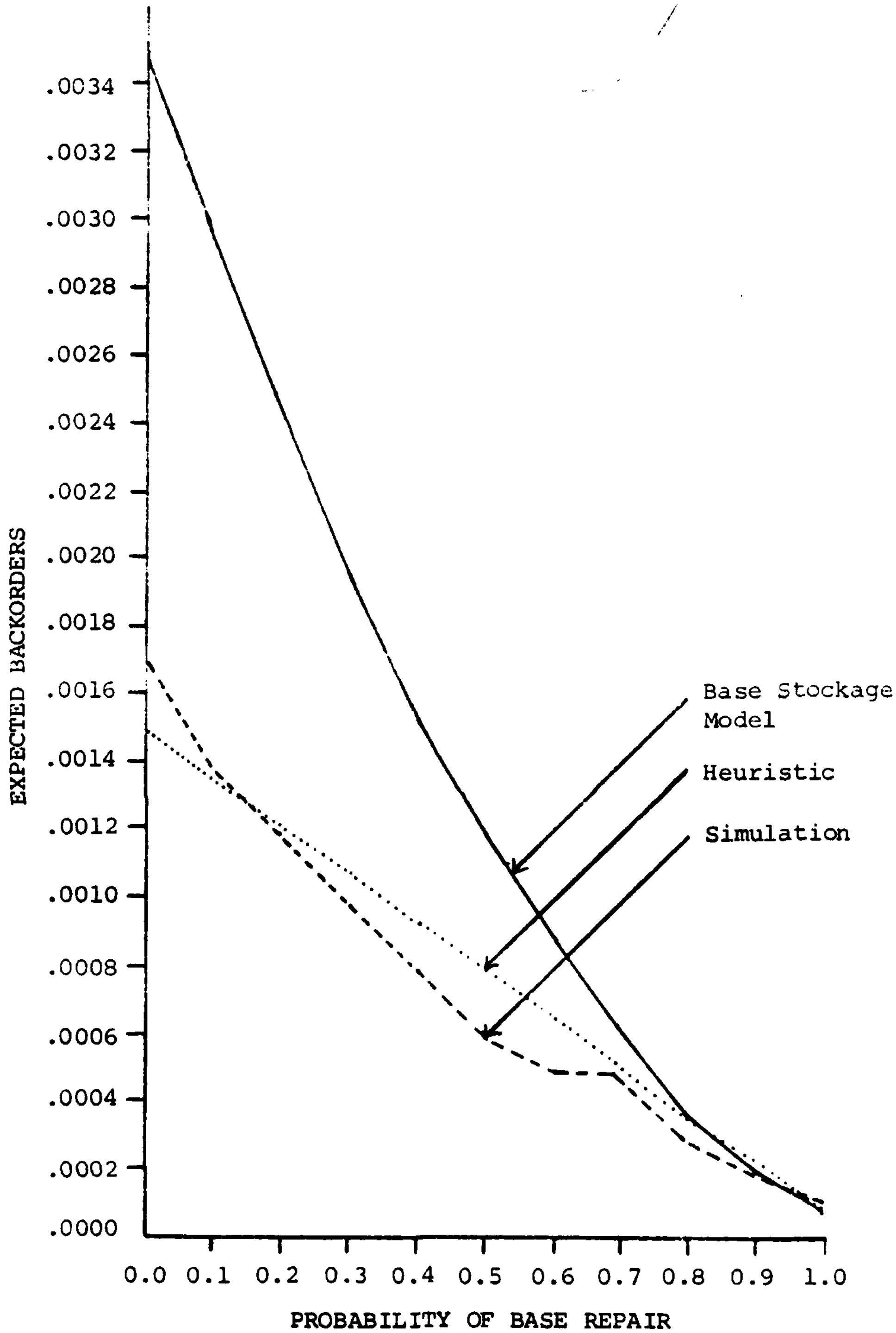

Fig. 8. A Comparison of Expected Backorders when Demand is One per Year

Model Optimization

The algorithm used (Eq 52) to calculate system availability:

$$SA = \prod_{i=1}^{n} \left(1 - \frac{E(B_i \mid S_i=1)}{N}\right) \qquad \text{(Eq 52)}$$

where (Eq 58) found the expected backorders given one unit was stocked. To find the system availability given that nothing was stocked, (Eq 58) was replaced in the system availability formula by:

$$E(B_i \mid S_i=0) = \lambda[(PBR)(RCT) + (1-PBR)(T_X)] \qquad \text{(Eq 59)}$$

When nothing was stocked, all demands were backordered; thus, the resupply was always expedited (T_X).

Ideally, inventory investment is optimized by maximizing system availability subject to a budget constraint. However, the availability product is a nonseparable function, thus an alternative objective function is:

$$\text{Max} \sum_{i=1}^{n} \ln\,(1-E(B_i \mid S_i=1)) \qquad \text{(Eq 60)}$$

Unfortunately, the decision maker does not have a priori knowledge of the appropriate budget constraint. Therefore, a benefit-to-cost ratio (BCR) was used to rank each item by its backorder reduction potential:

$$BCR = \frac{\log(1-E(B_i|S_i=0))-\log(1-E(B_i|S_i=1))}{C_p} \quad \text{(Eq 61)}$$

Following the generalized Lagrangian optimization technique, all the selected items were ranked by their BCR values, from largest to smallest. This sequenced the items in the most efficient investment order for any budgetary constraint.

The relationship between availability and unit price, or the implied penalty cost (IPC) for stocking an item was:

$$IPC_i = C_{pi}/(SA|S_i=1) - (SA|S_i=0) \quad \text{(Eq 62)}$$

The IPC was the marginal cost of system availability at the last inventory increment. The efficient investment ranking listed items from the lowest to the highest IPC. Each incremental purchase, while raising the overall system availability, became increasingly less cost-effective; that is, additional investment is only warranted if the penalty cost associated with end-item non-availability is increased. Appendix C lists the complete algorithm FORTRAN coding.

Sensitivity Analysis

The algorithm is most sensitive to changes in usage rates and resupply times, the two most critical item parameters. In Chapter IV, the heuristic backorder

estimate is compared to Palm's Theorem operating under two systems; one system expedites every resupply, the other allows only routine resupply. Also, the impact of incrementally increasing the routine resupply duration is tested. Finally, the sensitivity of expected backorders to usage rate variations is measured.

Summary

In this chapter, an alternative to current inventory models was developed. The algorithm was tailored for systems which were characteristically high-reliability, and low-density. Innovative features of the algorithm included consideration of expedited resupply, and three alternative methods to base inventory purchases upon. Chapter IV resports the algorithm results on the F-15 data base and its sensitivity to parameter variations.

CHAPTER IV

RESULTS

Introduction

This chapter discusses the general results of the application of the algorithm to the sample data base, the inefficiency of current Air Force stockage policies, and the results of sensitivity analysis. The sensitivity analysis focuses upon the two most critical input parameters, resupply time and usage rate estimates. The data from Eglin AFB, Florida were used for all sensitivity testing.

General Results

Algorithm Output

The algorithm output provides information needed by decision makers to solve base-level inventory investment problems. Appendix D lists the results for Eglin AFB, Florida.

The first value is the system availability when nothing is stocked. The second set of values result when each incremental unit is stocked. The eight data headings are:

1. ID--the inventory increment number.
2. ITEM--the item's position in the data set.

3. TOTAL BUDGET--the total inventory investment to that increment.

4. AVAIL--the system availability at that increment.

5. BEN/COST RATIO--the benefit of stocking an increment divided by the item's unit price.

6. PENALTY cost--the implied worth, in dollars per day, of system availability when that inventory increment is purchased.

7. ITEM NOMENCLATURE--the standardized item description.

8. NATIONAL STOCK NUMBER--the unique numeric designator identifying a specific inventory item.

The output format allows the base inventory manager three alternatives in selecting an appropriate stockage. First, the manager may stock to a fixed budget maximum. Second, the stockage may be based upon achieving a desired end-item availability. Finally, the stocking may continue until a relevant implied penalty cost is reached. As long as the recommended purchase sequence is followed, any of the alternatives will guarantee the most cost-effective inventory investment.

Base Comparisons

Table 7 compares the system availability level with the investment required to reach that point, for the

TABLE 7

SYSTEM AVAILABILITY AND THE ASSOCIATED INVENTORY INVESTMENT BY BASE

System Availability	Inventory Investment by Base				
	Nellis	Luke	Langley	Holloman	Eglin
.40	0	0	0	0	0
.45	1.78	0	6.95	0	0
.50	41.98	3.03	92.19	3.77	13.38
.55	197.25	54.95	263.85	64.35	116.70
.60	466.75	231.27	539.64	204.19	305.73
.65	921.30	512.08	1001.46	455.29	653.62
.70	2420.60	1150.23	2727.57	931.19	1286.35
.75	7969.81	4143.35	7969.81	2429.78	4450.32
.80	17076.83	11579.04	14562.83	8178.04	11579.04
.85	29206.21	20732.83	29206.21	17076.83	24784.83
.90	55012.80	42600.30	53760.10	36935.41	44710.54
.95	100697.74	81516.41	93635.96	78467.41	83436.97
.98	270253.94	134337.75	270253.94	145905.75	183040.75
.99	--	270253.94	--	270253.94	270253.94

five bases. The purchase sequence varied between the bases; however, most of the sequence changes were among items with extremely close benefit-to-cost ratios. Nevertheless, the overall purchase sequence did not differ radically between bases.

Table 8 compares the initial system availability with no stock to the final availability when every item was stocked. Each base began and ended with slightly different system availabilities. The difference was created by resupply time variations, since identical annual demands and base repair values were used by the algorithm for each base.

One trend that remained constant between bases was the incremental growth of the implied penalty cost. For Eglin AFB, Florida, the first one thousand dollars in the budget purchased sixty items, each with a very low implied penalty cost:

Increment	Total Budget	Implied Penalty Cost
32	$ 204	$ 10
43	405	18
55	796	30
60	1001	34
79	2051	140
82	2728	203

As the comparatively less expensive items were stocked, the implied penalty cost began to grow more rapidly.

TABLE 8

A COMPARISON OF SYSTEM AVAILABILITY BY BASE GIVEN NO STOCK AND FULL STOCK

	SYSTEM AVAILABILITY				
	Air Force Base				
Inventory Investment	Eglin	Holloman	Langley	Luke	Nellis
\$ 0.00 (no stock)	.4499	.4665	.4111	.4784	.4311
\$270,253.94 (full stock)	.9836	.9857	.9806	.9866	.9740

Algorithm Validation

Chapter III demonstrated that applying an inventory technique utilizing a single mean resupply time significantly misestimated expected system backorders (Figure 5). A similar test was performed upon the algorithm to determine if the results for expected backorders extended to system availability.

The test compared the system availability produced at specific budget levels under three policies:

1. A policy of dual resupply priorities.
2. A policy of always expediting resupply.
3. A policy of never expediting resupply.

Table 9 lists the results. Although the budget increments are uneven, they were selected due to their commonality to every output listing. Figure 9 portrays the difference in system availability produced at different

TABLE 9

A COMPARISON OF THE SYSTEM AVAILABILITY FROM INVESTMENT UNDER THREE DIFFERENT RESUPPLY POLICIES

Inventory Investment	System Availability Policy: Always Routine	Dual-Priority (Heuristic)	Always Expediting
0.00	.1015	.4499	.4499
204.19	.2114	.5769	.5799
405.32	.2583	.6181	.6220
795.72	.3198	.6653	.6703
1,001.46	.3440	.6823	.6876
1,367.96	.3750	.7022	.7079
1,714.16	.3899	.7117	.7175
2,122.81	.4029	.7199	.7258
4,450.32	.4569	.7502	.7570
9,757.04	.5281	.7906	.7986
31,451.41	.6895	.8732	.8835
76,743.28	.8460	.9411	.9530
91,160.96	.8842	.9551	.9672
109,047.74	.9208	.9681	.9805
134,337.75	.9422	.9758	.9883
183,040.75	.9534	.9798	.9924
270,253.94	.9644	.9836	.9962

AD-A123 789 A SPARES STOCKAGE ALGORITHM FOR LOW-DENSITY EQUIPMENT (U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF SYSTEMS AND LOGISTICS G C PANKONIN ET AL. 2/2

UNCLASSIFIED SEP 82 AFIT-LSSR-33-82 F/G 15/5 NL

END

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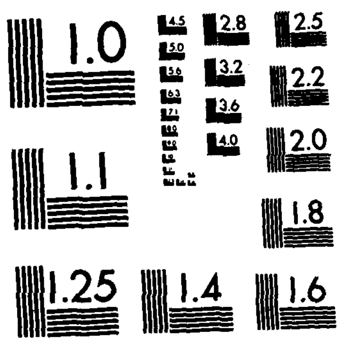
DTIC



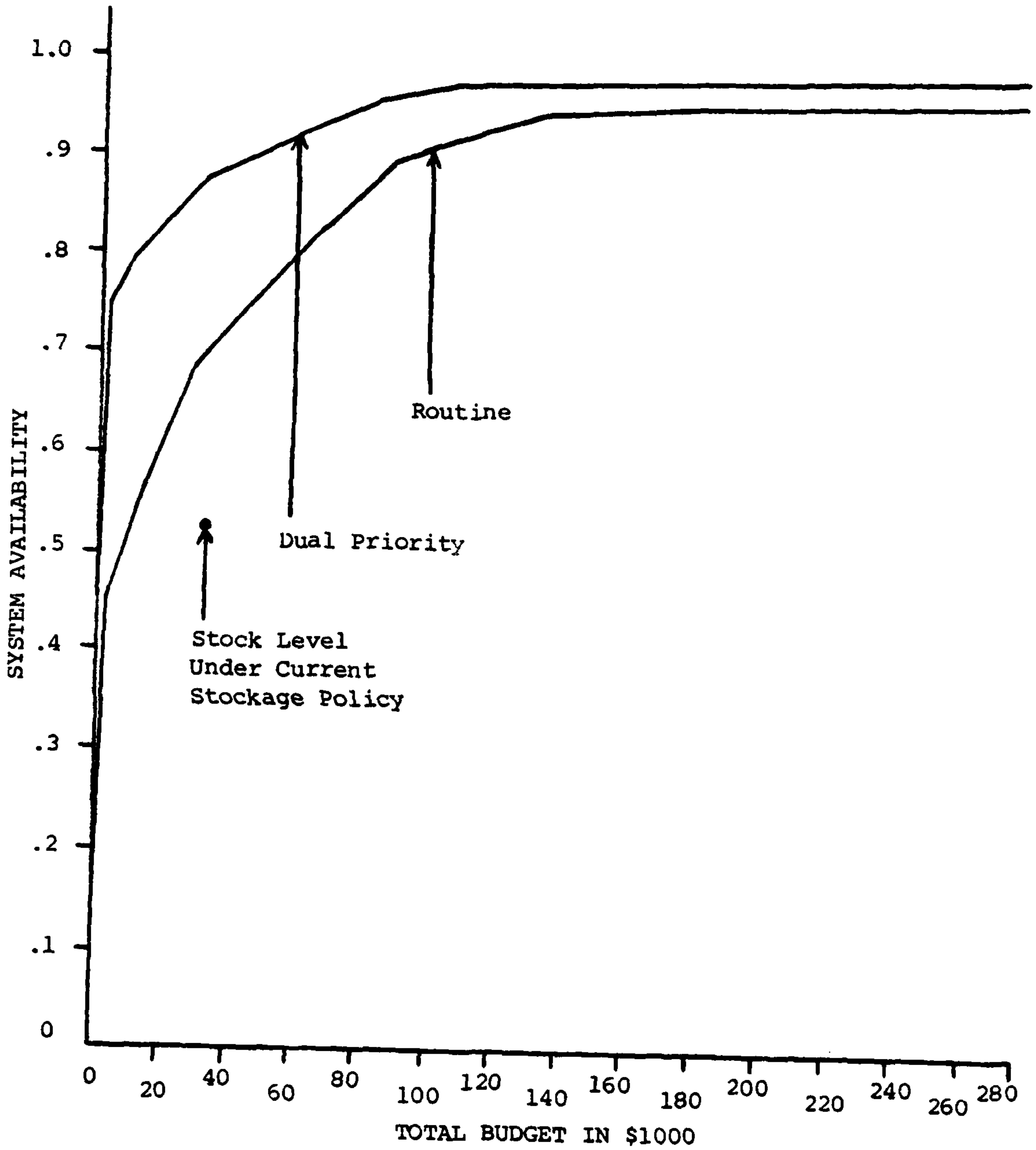


Fig. 9. System Availability from Identical Investments for Two Different Resupply Policies--Entire Investment Range

investment levels by the algorithm and routine policy. Note that although the expediting policy results were always slightly higher than the algorithm, this difference was not distinguishable in Figure 9. Figure 10 is an enlargement of Figure 9 for inventory investments up to $10,000. This region contained the most dramatic increases in system availability for small inventory investments.

Air Force Policy

Current Air Force policy is not designed to authorize the base-level stockage of very low-demand items. Generally, external management actions are required to stock low-demand items at base-level. The motivation for such actions is often varied and disjointed.

Fifteen of the sample items (Table 2) were stocked at Eglin AFB, Florida. Their total value was $32,115; their stockage provided a 52.6 percent system availability. This point is shown in Figure 9. Located below the optimality curve, the point represents an inefficient solution to the inventory problem.

The algorithm shows that the decision maker has two basic alternatives. First, for a much smaller investment ($200), the same system availability may be reached. Secondly, the current investment could provide a much higher system availability (.8700) by following the

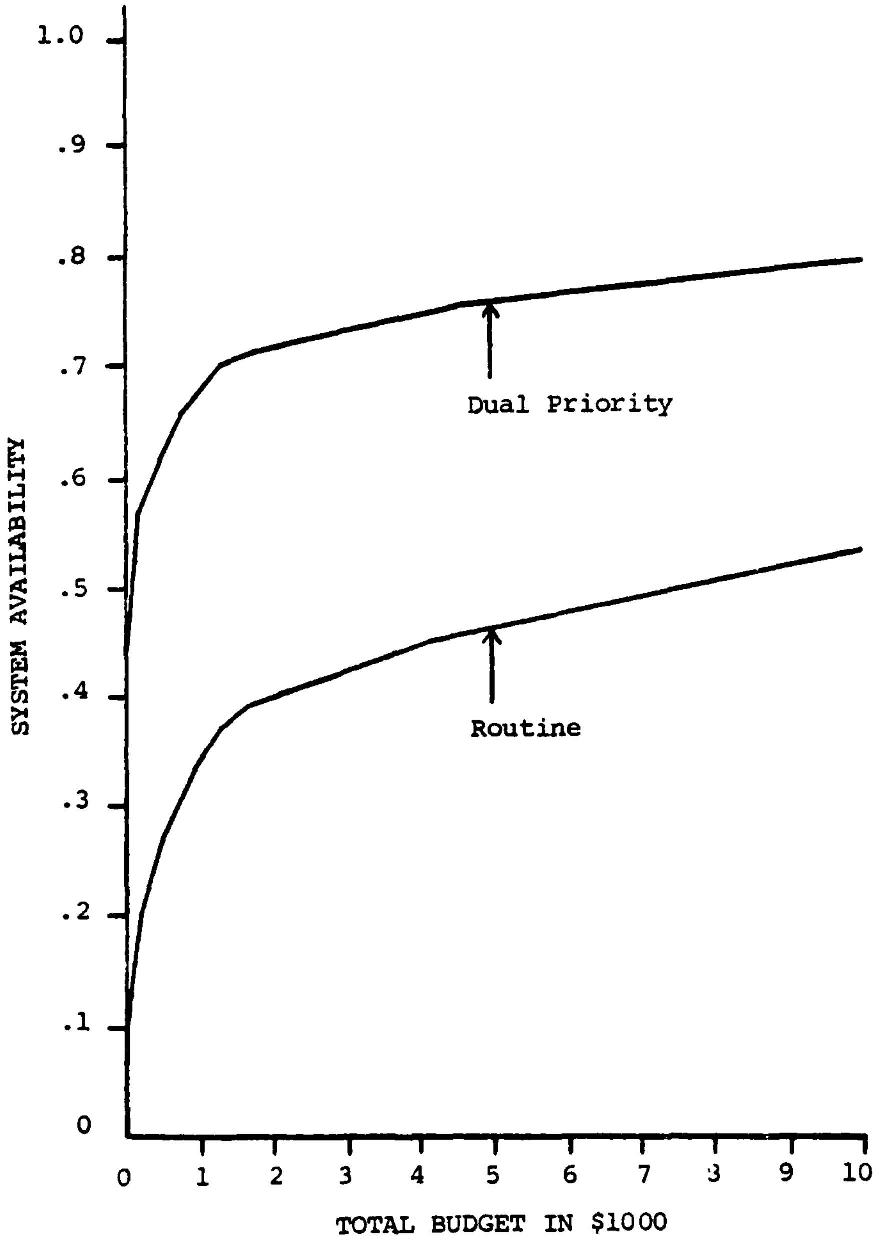


Fig. 10. System Availability from Identical Investments for Two Different Resupply Policies--First $10,000 Invested

algorithm purchase sequence. Either decision is a more efficient and direct answer to the inventory problem.

Sensitivity Analysis

Two tests measured the sensitivity of the algorithm to variations in critical parameters. The first test measured order and shipping time (OST) sensitivity, the second test measured usage rate sensitivity.

OST Sensitivity

This test measured the impact of incrementally increasing resupply time upon system availability. The routine resupply times were tested since they demonstrated the greatest variance in the original OST data (Table 1). The times were varied from ten to thirty days in five-day increments.

Table 10 compares the required inventory investment at specific system availabilities, across the five resupply time values. Figure 11 depicts the system availability at specific budget levels for the extreme cases, ten and thirty days.

As the routine resupply time increased, the investment required to reach the same system availability also increased. The difference in required investment became especially noteworthy at the 90 percent availability level, where the resupply times required investments ranging from $40,000 to $48,000. However, only five

TABLE 10

A COMPARISON OF THE INVESTMENT REQUIRED TO REACH SPECIFIC AVAILABILITY LEVELS FOR FIVE RESUPPLY TIME VALUES

System Availability	Routine Resupply Duration (Days)				
	10	15	20	25	30
.40	0	0	0	0	0
.45	0	0	0	0	0
.50	9.08	9.08	9.08	9.08	9.08
.55	99.09	99.09	99.09	99.09	116.70
.60	263.85	288.00	288.00	288.00	293.88
.65	577.15	637.76	647.97	647.97	647.97
.70	1150.23	1196.30	1252.41	1286.35	1367.96
.75	3577.32	4450.32	4450.32	4450.32	4597.94
.80	9757.04	9757.04	11579.04	11579.04	11579.04
.85	20732.83	20732.83	20732.83	24784.83	24784.83
.90	40004.41	41602.60	43650.16	44710.54	48202.27
.95	75110.95	78467.41	83436.97	89207.09	93535.96
.98	112449.74	125562.75	183040.75	270253.94	270253.94
.99	270253.94	270253.94	270253.94	--	--

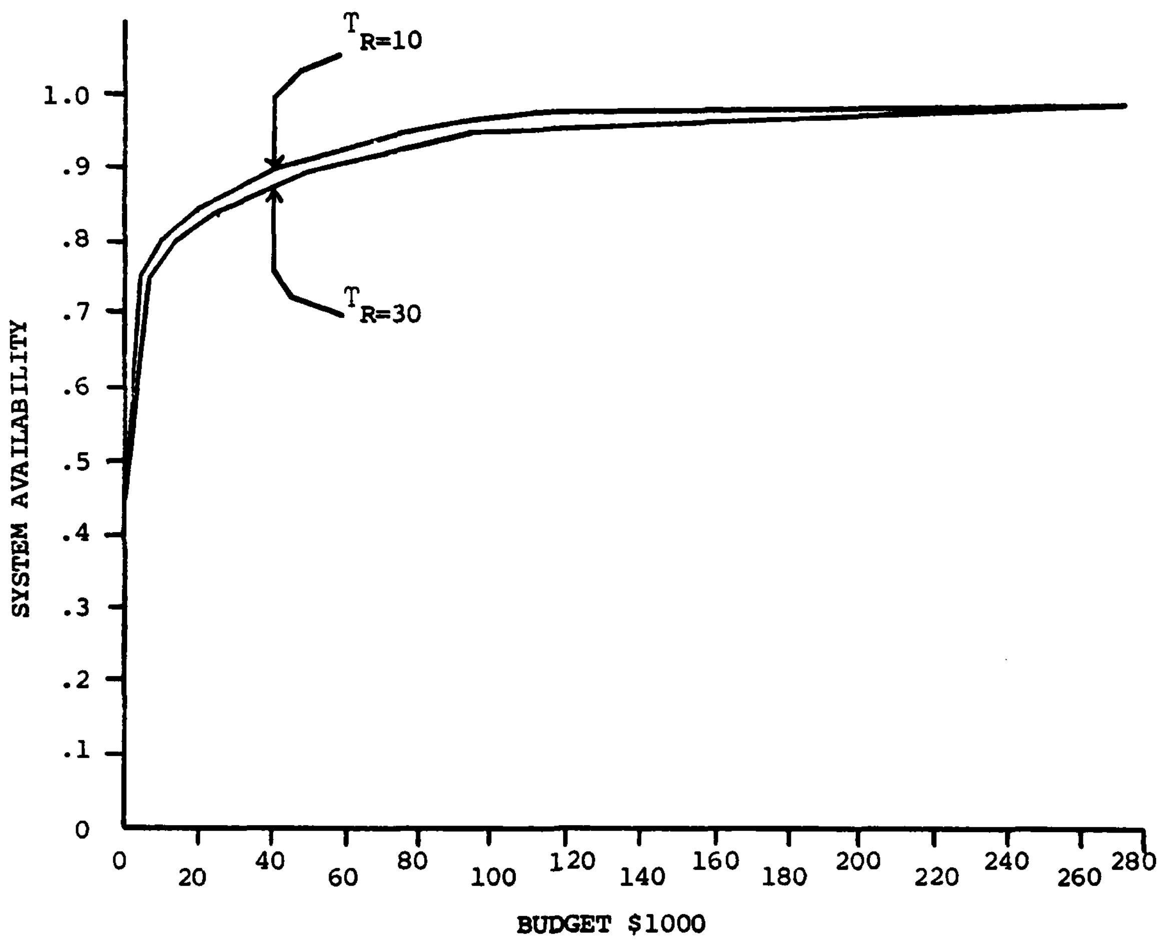


Fig. 11. System Availability at Specific Investment Levels for Two Routine Resupply Time Durations

inventory increments separated the two extreme resupply times and investments.

The incremental resupply times produced a narrow band of system availabilities for any specific inventory investment. Even with a 200 percent change in the resupply time, the results were tightly grouped and significantly different from assuming a single mean resupply time (Figure 9).

Usage Rate Sensitivity

Identical, pooled estimates of usage rates were used to develop the purchase sequence list for each base. To test the usage rate sensitivity, the demands for each item were multiplied by constant factors simulating consistent estimation errors. The four constant error factors were: (1) 2.0, (2) 1.5, (3) 0.75, and (4) 0.50. Table 11 compares, for each factor, the system availability resulting from specific investments. Figure 12 portrays the results over the entire investment range; Figure 13 presents the same results for investments up to $10,000.

If the true demand was less than the estimate (0.75 and 0.50), then the system availability at any inventory position was underestimated and expected backorders overestimated. If the true demand was greater than the estimate (2.0 and 1.5), then the system availability

TABLE 11

THE SYSTEM AVAILABILITY FROM SPECIFIC INVESTMENT LEVELS FOR DIFFERENT DEMAND ERROR MAGNITUDES

Inventory Investment	Error Magnitude				
	2.0	1.5	Actual	0.75	0.50
$ 0	.2009	.3009	.4499	.5498	.6714
204.19	.3270	.4353	.5769	.6631	.7612
405.32	.3746	.4824	.6181	.6984	.7882
795.72	.4331	.5382	.6653	.7382	.8180
1001.46	.4552	.5589	.6823	.7524	.8284
1367.96	.4819	.5834	.7022	.7688	.8405
1714.16	.4949	.5952	.7117	.7766	.8461
2122.81	.5063	.6055	.7199	.7833	.8510
4450.32	.5488	.6436	.7502	.8080	.8689
9757.04	.6083	.6958	.7906	.8406	.8922
31,451.41	.7399	.8067	.8732	.9059	.9380
76,743.28	.8583	.9022	.9411	.9584	.9740
91,160.96	.8837	.9222	.9551	.9690	.9812
109,047.74	.9079	.9412	.9681	.9790	.9880
134,337.75	.9223	.9524	.9758	.9848	.9919
183,040.75	.9299	.9583	.9798	.9879	.9939
270,253.94	.9370	.9637	.9836	.9907	.9958

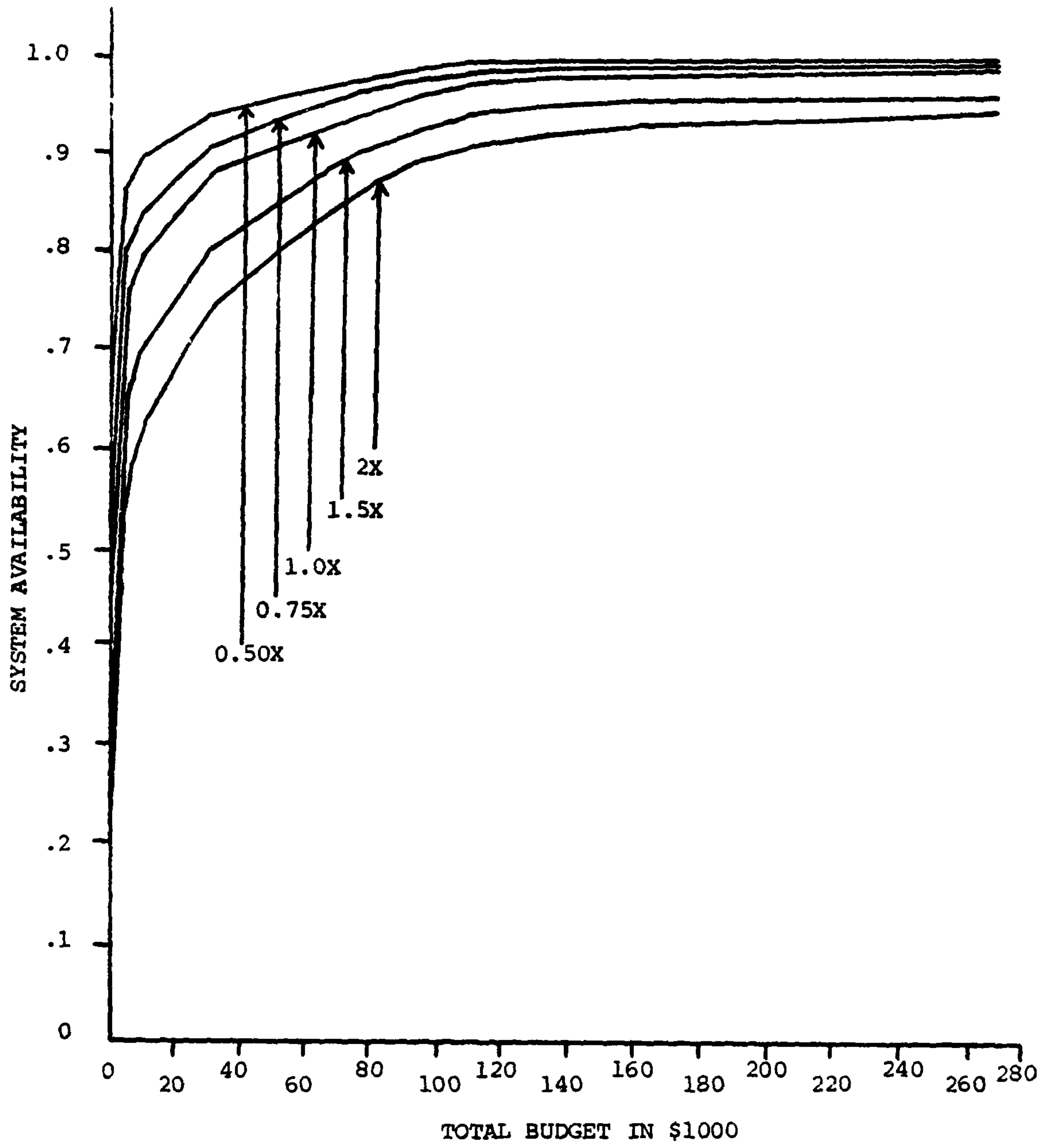


Fig. 12. System Availability versus Total Budget for Five Levels of Demand--Entire Investment Range

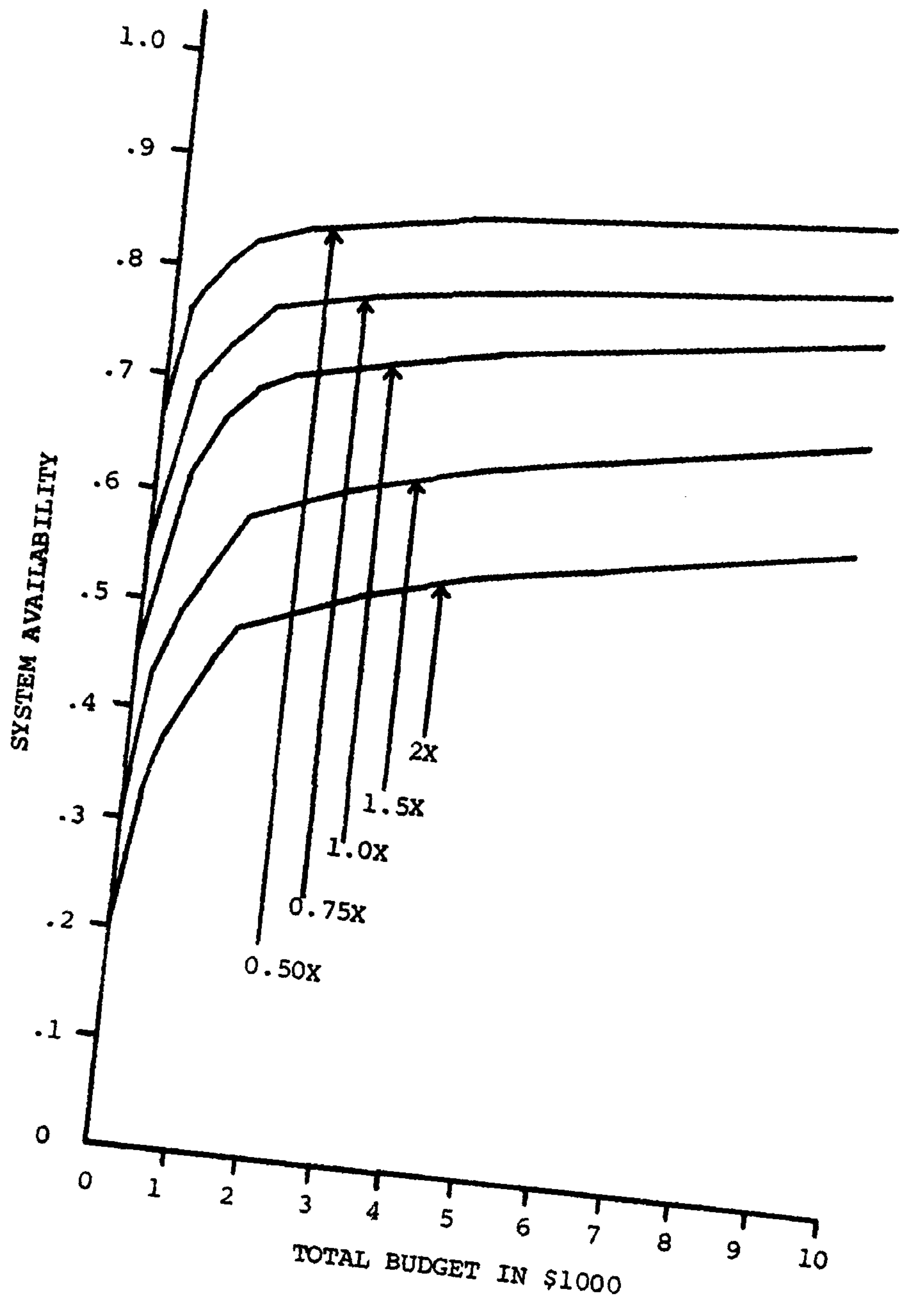


Fig. 13. System Availability versus Total Budget for Five Levels of Demand--First $10,000 Invested

at any inventory position was overestimated and expected backorders underestimated.

Underestimating demands by one-half (2.0) yielded system availabilities comparable to never expediting in the algorithm validation (Figure 9). Overestimating demands by twofold (0.50) yielded higher system availabilities than always expediting, at almost every investment level. Doubling and halving demands provide the decision maker with approximate boundaries to gauge proposed inventory investments. Minor sequence changes continued as the demand estimates are varied; however, the overall purchase sequence remained fairly constant.

Summary

The general algorithm ranks items in their most cost-effective purchase sequence. The decision maker may base the stockage decision on three alternative criteria: (1) system availability, (2) total budget, or (3) the implied penalty cost. The item ranking varies slightly by base, yielding slightly differing availabilities. The implied penalty cost of purchasing an additional stock increment grows very slowly, while the item's unit price is low. However, as the unit price increases more dramatically, the implied penalty cost begins to grow rapidly. Inventory techniques incorporating a single mean

resupply time misestimate the system availability provided by a dual priority system.

The current Air Force policy provides an inefficient stockage of low-demand items. The algorithm offers two basic alternatives: (1) provide the same availability for a smaller investment, or (2) achieve a higher availability for the same investment.

The resupply time sensitivity analysis demonstrates that the longer the resupply time, the greater the investment required to maintain the same system availability. However, even a tripling of the resupply time results in a tight range of system availabilities. The usage rate sensitivity analysis demonstrates that: (1) when the actual demand is overestimated system availability is underestimated, and (2) when the actual demand is underestimated system availability is overestimated. In general, it appears that the algorithm is much more sensitive to the estimate of demand than resupply time.

CHAPTER V

SUMMARY AND CONCLUSIONS

Research Summary

When weapon systems are developed, it is difficult to forecast the exact spares stockage required to achieve a desired system availability. Traditionally, spares funding has been severely limited; the funding is still inadequate, and will probably remain that way. With insufficient funding, effective and efficient spares stockage becomes more vital to achieving and maintaining a high system availability. Unfortunately, current demand-driven inventory policies recommend inefficient spares stockage of low-demand items.

From these issues, three research questions were developed. First, what would be an alternative cost-effective stockage policy for low-density, high-reliability equipment? Second, how would the alternative policy compare with current Air Force policies? Third, how sensitive would the alternative policy be to data variations?

The alternative stockage algorithm was tailored to systems possessing several characteristics. Only one end-item was supported per base; the system had no built-in redundancy. All items were equally essential and

mission critical; the system required only one unit of the item. Item demands were independent and assumed a Poisson distribution with a mean usage rate of one per year or less.

The item demand and repair histories from several bases were pooled and averaged to obtain more accurate parameter estimates. Total system backorders were found as a weighted average of the backorders due to base repair and depot resupply. The depot resupply portion explicitly considered the use of priority transportation for NMCS requirements. The total expected system backorders were converted into expected system availability, and then used to rank items in their most cost-effective purchase sequence. This ranking allows the inventory manager to base stockage decisions upon: (1) total budget, (2) system availability, or (3) the implied penalty cost of an NMCS system.

The item purchase sequence varied slightly between the bases. At each base, an equal inventory investment bought a slightly different amount of system availability. The current Air Force stockage policies result in an inefficient stockage position, located below the optimal stockage curve. As resupply time increased, a greater inventory investment was required to maintain a specific system availability level. Multiplying the item demands

by variable factors provides approximate system availability boundaries for comparative analysis.

Research Conclusions

The research demonstrated that explicitly considering the dual Air Force resupply priority policy more accurately represents system availability than following a single resupply time assumption. Adhering to a non-expediting policy significantly underestimated system availability. This suggests that inventory managers may commit a serious error when the impact of priority resupply is neglected. Expediting every resupply provided only a marginal increase in system availability. This implies that the Air Force policy for assigning resupply priorities is effective. For low-demand items, expediting without exception appears to be cost-prohibitive.

Although the true, or optimal, implied penalty cost was not established, the results indicate that the penalty of purchasing an additional increment grows very slowly, at first. Most inventory managers would probably agree that it is worth an additional \$18 or \$34 to gain an additional day of test station availability. Purchasing 60 items for \$1000 is a very inexpensive way to increase a test station's availability by 23 percent. Since the algorithm implicitly assumes that each base purchases a new inventory every year, the implied penalty costs are

conservative. The very nature of low-demand items implies that only a few will need to be replaced. Thus, a sizeable savings is realized.

The current demand-driven stockage of low-demand items is inefficient. This is caused by the myopic base stockage policy. Any single base does not have a broad enough perspective to see the true usage rates of low-demand items. Thus, items which the current policies stock cannot represent the most cost-effective purchases.

The research demonstrated that considering the dual resupply policy enhanced the estimation of expected backorders and system availability. Variations in the resupply duration result in narrow bands of system availability at any inventory investment. This implies that the algorithm is relatively insensitive to errors in the estimation of resupply time values. Misestimating usage rates by large amounts creates significant changes in system availability. Multiplying demands by constant factors can provide the decision maker with approximate confidence boundaries to evaluate proposed inventory investments.

Methodological Issues

Five significant methodological questions arose during the research. Initially, the HQ TAC D-165 data included duplicate item demands caused by policies unique to certain bases. Secondly, no reliable method was found

to ensure that each selected item in the data set was peculiar to the F-15 AIS. Next, the order and shipping times were collected in FY 1982, but were assumed to closely resemble the FY 1981 times. Fourth, the algorithm assumed there was no built-in redundancy in the F-15 AIS, and that only one unit of each item was used on the system. Finally, the algorithm assumed that only one F-15 AIS was supported by each base. However, the actual number of test stations per base ranged from one to three.

Suggestions for Future Research

The current research effort suggested three possible areas for future research:

1. Define and locate what a reasonable implied penalty cost stopping point would be. Since the F-15 AIS is a "spares multiplier," what is the worth of failed LRUs and delayed repairs, when the test station is NMCS?

2. Adapt the algorithm for bases supporting multiple test stations. The impact of parts cannibalization must be expressly considered.

3. Apply the current algorithm to field data from other low-density, high-reliability systems.

Recommendations

The F-15 is America's first-line air-superiority fighter, whose mission performance is heavily dependent upon its on-board avionics systems. The F-15 AIS is

effectively a spares multiplier for this $19 million aircraft (Ref 14). When the AIS becomes inoperational for a part costing as little as one cent, the repair of scarce avionics components is delayed, and degradation of the air-superiority mission may result.

The algorithm is ready to be implemented at the major command level on a test basis; the F-15 AIS is the logical field trial system. For extremely low-demand items, the algorithm is far superior to current demand-driven policies. Considering the number of F-15 AIS NMCS incidents in FY 1981 resulting from inadequate stockage of low-demand items, the algorithm should be given an opportunity to demonstrate its potential.

APPENDICES

APPENDIX A

Q-GERT SIMULATION CODING

```
GEN,PANKOPETE,QGERT1,9,29,1982,,1,100,,100,,,1*
SOU,10/SOURCE,0,1,D,M*
REG,11/USERFUNC,1,1,D*
REG,12/DIVIDER,1,1,D*
QUE,5/ORDER-Q,0,,D,F,(10)9*
QUE,15/ASSET-Q,1,,D,F,(10)9*
SEL,9,ASM,,,,5,15*
SIN,20/SINK,1,1,D,I*
REG,13/COND,1,1,F*
VAS,11,1,UF,1*
ACT,10,11,,,2*
ACT,10,10,EX,1,1*
ACT,11,12,,,3*
ACT,12,5,,,4*
ACT,12,13,,,5*
ACT,13,15,NO,2,6/LONG,,,A1.EQ.1*
ACT,13,15,NO,3,7/SHORT,,,A1.EQ.2*
ACT,9,20,CO,0.01,8,1*
PAR,1,182.5,0.,730.*
PAR,2,31.,10.,50.,10.*
PAR,3,8.,6.,14.,2.*
FIN*
```

APPENDIX B

MODIFIED Q-GERT PROGRAMMING

```
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SOU,10/SOURCE,0,1,D,M*
REG,11/USERFUNC,1,1,D*
REG,12/DIVIDER,1,1,D*
QUE,5/ORDER-Q,0,,D,F,(10)9*
REG,14/REPAIR,1,1,P*
QUE,15/ASSET-Q,1,,D,F,(10)9*
SEL,9,ASM,,,,5,15*
SIN,20/SINK,1,1,D,I*
REG,13/COND,1,1,F*
VAS,11,1,UF,1*
ACT,10,11,,,2*
ACT,10,10,EX,1,1*
ACT,11,12,,,3*
ACT,12,5,,,4*
ACT,12,14,,,5*
ACT,14,15,EX,4,9,(8)0.30*
ACT,14,13,,,10,(8)0.70*
ACT,13,15,NO,2,6/LONG,,,A1.EQ.1*
ACT,13,15,NO,3,7/SHORT,,,A1.EQ.2*
ACT,9,20,CO,0.01,8,1*
PAR,1,182.5,0.,730.*
PAR,2,31.,10.,50.,10.*
PAR,3,8.,6.,14.,2.*
PAR,4,5.,2.,8.*
FIN*
```

APPENDIX C

FORTRAN PROGRAM CODING

```
      PROGRAM LOWDEN
      DIMENSION AD(150),PBR(150),BRT(150),UC(150),NDC(150)
      DIMENSION STM(10,10,3),PST(150),RST(150),TE(150)
      DIMENSION EBZ(150),EB1(150),BCR(150),NPOINT(150),SV(150)
      DIMENSION NSN(150,4),NOMEN(150,5)
      CHARACTER NOMEN*4
      CHARACTER NSN*4
1     WRITE(60,100)
      REWIND 70
      REWIND 80
100   FORMAT(1H1,"HOW MANY ITEMS ?")
      READ(60,*)NITEM
      WRITE(60,101)
101   FORMAT(1H1,"WHAT BASE CODE ?")
      READ(60,*)NBASE
      IF (NBASE.EQ.0) THEN
      STOP
      END IF
C
C   DO LOOP 10 - READ IN SHIPPING TIME FILE; BASES I, DEPOTS J
C
      DO 10 I=1,5
      DO 10 J=1,8
10    READ(70,102)(STM(I,J,K),K=1,3)
102   FORMAT(3F10.2)
C
C   DO LOOP 20 - READ IN ITEM DATA
C
      DO 20 I=1,NITEM
      READ(80,103)(NSN(I,J),J=1,4),AD(I),NDC(I),PBR(I),BRT(I),UC(I),
     *(NOMEN(I,J),J=1,5)
103   FORMAT(A4,A3,A4,1X,A4,F3.0,6X,I1,3X,F4.2,F5.1,F9.2,2X,5A4)
20    CONTINUE
C
C   DO LOOP 30 - CHECK AND APPORTION DEMANDS, ASSIGN SHIPPING TIMES
C
      DO 30 I=1,NITEM
      IF(AD(I).LE.0)AD(I)=1.0
      AD(I)=AD(I)/(365.0*10.0)
      PST(I)=STM(NBASE,NDC(I),1)
```

```
      RST(I)=STN(NBASE,NDC(I),3)
30    NPOINT(I)=I
      SAV=1.0
C
C   DO LOOP 40 - COMPUTE SYSTEM AVAILABILITY WITH NO STOCK
C
      DO 40 I=1,NITEM
      EB=AD(I)*((PBR(I)*BRT(I))+((1.0-PBR(I))*PST(I)))
      SAV=SAV*(1.0-EB)
40    EBZ(I)=EB
      WRITE(60,104) SAV
      PRINT *
      WRITE(60,110)
      PRINT *
104   FORMAT(1H1,20X,"SYSTEM AVAILABILITY WITH NO STOCK",3X,
     *F6.4,2X,"(PROB)")
110   FORMAT(1H1,24X,"SYSTEM AVAILABILITY WITH STOCK OF ONE")
C
C   DO LOOP 50 - COMPUTE EFFECTIVE RESUPPLY TIME
C
      DO 50 I=1,NITEM
      TEE=1.0/((1.0/RST(I))+(1.0/PST(I)))
      TED=((2*RST(I)*PST(I))-(PST(I)**2))/(2*RST(I))
      TE(I)=(TEE+TED)/2.0
50    CONTINUE
C
C   DO LOOP 60 - COMPUTE EXPECTED BACKORDERS & BENEFIT/COST RATIO
C
      DO 60 I=1,NITEM
      X=AD(I)*PBR(I)*BRT(I)
      Z=AD(I)*(1.0-PBR(I))
      EB1(I)=(X-1.0+EXP(-X))+(Z*(1.0-EXP(-Z*RST(I)))*TE(I))
      BCR(I)=(EBZ(I)-EB1(I))/UC(I)
60    SV(I)=BCR(I)
C
C   DO LOOPS 70 & 80 - SORTING PROCEDURE
C
      DO 80 NPASS=1,NITEM
      NSW=0
      DO 70 I=1,(NITEM-NPASS)
```

```
      F=SV(I)
      S=SV(I+1)
      IF(F.GT.S) GO TO 70
      SV(I)=S
      SV(I+1)=F
      NF=NPOINT(I)
      NS=NPOINT(I+1)
      NPOINT(I)=NS
      NPOINT(I+1)=NF
      NSW=NSW+1
70    CONTINUE
      IF(NSW.EQ.0) GO TO 81
80    CONTINUE
81    SPENT=0
      WRITE(60,105)
      WRITE (60,107)
      WRITE(60,150)
105   FORMAT (1X,11X,'TOTAL',4X,'AVAIL',2X,'BEN/COST',2X,
     *'PENALTY',24X,'NATIONAL')
107   FORMAT (1X,2X,'ID',1X,'ITEM',2X,'BUDGET',2X,'(PROB)',
     *3X,'RATIO',5X,'COST',4X,'NOMENCLATURE',10X,'STOCK',
     *1X,'NUMBER')
C
C   DO LOOP 90 - COMPUTE NEW SYSTEM AVAILABILITY & PENALTY COST
C
      DO 90 I=1,NITEM
      N=NPOINT(I)
      SAVN=SAV*(1.0-EB1(N))/(1.0-EBZ(N))
      PCOST=UC(N)/(365*(SAVN-SAV))
      SAV=SAVN
106   FORMAT (1H,I3,2X,I3,1X,F9.2,1X,F5.4,1X,F9.7,1X,F9.2,
     *1X,5A4,2X,A4,A3,A4,1X,A4)
      SPENT=SPENT+UC(N)
      WRITE(60,106)I,N,SPENT,SAV,BCR(N),PCOST,(NOMEN(N,J),J=1,5),
     *(NSN(N,J),J=1,4)
150   FORMAT ('+',85('_'))
90    CONTINUE
      GO TO 1
      STOP
      END
```

APPENDIX D

ALGORITHM RESULTS

SYSTEM AVAILABILITY WITH NO STOCK 0.4499 (PROB)

SYSTEM AVAILABILITY WITH STOCK OF ONE

ID	ITEM	TOTAL BUDGET	AVAIL (PROB)	BEN/COST RATIO	PENALTY COST	NOMENCLATURE	NATIONAL STOCK NUMBER
1	49	0.01	.4559	1.2981084	0.00	WASHER,LOCK	5310 00 224 0748
2	50	0.49	.4610	0.0232916	0.26	NUT,SELF LOCKING	5310 00 894 3637
3	117	0.89	.4645	0.0188526	0.31	CONTACT,ELECTRICAL	5999 00 902 3652
4	111	1.16	.4663	0.0140773	0.42	INSULATION SLEEVING	5970 01 009 7664
5	70	1.47	.4681	0.0122674	0.48	BUSHING ELECTRICAL	5935 00 167 7732
6	108	1.78	.4699	0.0122674	0.48	SEMI-CONDUCTOR DEVIC	5961 00 026 8889
7	118	2.52	.4734	0.0101906	0.57	CONTACT,ELECTRICAL	5999 01 006 2495
8	103	3.77	.4788	0.0089582	0.64	FERRULE,METALLIC SH	5940 00 581 7273
9	113	6.61	.4878	0.0064710	0.87	CONTACT,ELECTRICAL	5999 00 080 9726
10	112	6.95	.4887	0.0056165	1.00	CONTACT,ELECTRICAL	5999 00 062 5218
11	85	9.08	.4933	0.0044066	1.26	CONNECTOR RECEPTACL	5935 00 577 0011
12	116	13.38	.5017	0.0038628	1.41	CONTACT,ELECTRICAL	5999 00 824 5052
13	90	16.09	.5064	0.0034635	1.56	CONNECTOR PLUG,ELEC	5935 01 013 4453
14	119	16.83	.5074	0.0025805	2.09	CONTACT,ELECTRICAL	5999 01 048 3708
15	109	17.95	.5084	0.0017050	3.16	MICROCIRCUIT,DIGITA	5962 00 503 8035
16	92	26.11	.5132	0.0011503	4.64	CONNECTOR PLUG,ELEC	5935 01 027 6464
17	110	30.44	.5154	0.0010030	5.30	MICROCIRCUIT,DIGITA	5962 00 559 9775
18	87	41.98	.5213	0.0009719	5.41	CONNECTOR,PLUG,ELEC	5935 00 715 2756
19	139	44.18	.5223	0.0008675	6.05	METAL BAR	9510 00 293 4962
20	55	46.61	.5233	0.0007858	6.66	RESISTOR FIXED,WIRE	5905 00 404 8777
21	48	71.11	.5334	0.0007722	6.65	CONNECTOR	4935 01 030 5979
22	54	73.70	.5344	0.0007373	6.95	RESISTOR,FIXED,WIRE	5905 00 314 3327
23	115	76.32	.5354	0.0007289	7.02	CONTACT,ELECTRICAL	5999 00 766 9566
24	56	79.05	.5364	0.0006995	7.30	RESISTOR,FIXED,WIRE	5905 00 471 4426
25	86	99.09	.5435	0.0006502	7.75	CONNECTOR PLUG,ELEC	5935 00 593 9592
26	53	116.70	.5497	0.0006349	7.85	SPRING,HELICAL,COMP	5360 00 467 0351
27	96	134.30	.5556	0.0006083	8.10	CONNECTOR PLUG,ELEC	5935 01 048 0076
28	65	144.27	.5588	0.0005697	8.61	SWITCH,TOGGLE	5930 00 457 7273
29	71	173.72	.5682	0.0005640	8.54	CONNECTOR RECEPTACL	5935 00 194 1722
30	7	180.66	.5704	0.0005477	8.77	HOSE PREFORMED	4720 00 309 2652
31	57	184.58	.5715	0.0004871	9.84	CAPACITOR,FIXED	5910 00 230 7650
32	93	204.19	.5769	0.0004786	9.92	CONNECTOR RECEPTACL	5935 01 037 8220
33	77	231.27	.5834	0.0004142	11.33	CONNECTOR BODY,RECE	5935 00 434 2962
34	76	263.85	.5912	0.0003999	11.58	CONNECTOR PLUG,ELEC	5935 00 430 4102
35	73	288.00	.5968	0.0003807	11.81	CONNECTOR PLUG ELEC	5935 00 365 5623
36	106	293.88	.5979	0.0003248	14.11	RELAY,ELECTROMAGNETI	5945 01 027 3893
37	129	305.73	.6002	0.0003207	14.23	LENS,SWITCH ACTVATI	6210 00 385 9049
38	104	318.01	.6025	0.0003097	14.68	RELAY,ELECTROMAGNET	5945 00 404 8608
39	84	354.52	.6093	0.0003072	14.63	CONNECTOR,PLUG,ELEC	5935 00 543 1713
40	88	383.47	.6146	0.0002972	14.99	CONNECTOR,RECEPTACL	5935 01 007 0527
41	6	390.43	.6158	0.0002743	16.22	FILTER ELEMENT	4310 01 030 4239

42	67	397.53	.6169	0.0002690	16.51	CONNECTOR PLUG,ELEC	5935 00 063 9010
43	102	405.32	.6181	0.0002451	18.09	TERMINAL,MALE PLUG	5940 00 579 4981
44	81	438.07	.6228	0.0002303	19.10	CONNECTOR RECEPTACL	5935 00 525 5847
45	82	455.29	.6252	0.0002208	19.84	CONNECTOR BODY,RECE	5935 00 529 0232
46	1	473.19	.6276	0.0002123	20.56	NOZZL ASY FUE	2910 00 110 9692
47	127	482.26	.6288	0.0002105	20.70	LENS,SWITCH ACTVATI	6210 00 337 4034
48	132	557.54	.6383	0.0001970	21.78	DELAY LINE	6625 00 498 4836
49	51	577.15	.6407	0.0001938	22.06	PIN,SHOULDER,HEAD	5315 01 107 2359
50	95	643.41	.6490	0.0001930	21.86	CONNECTOR RECEPTACL	5935 01 046 9754
51	128	653.62	.6502	0.0001870	22.53	LENS,SWITCH ACTVATI	6210 00 343 7076
52	75	714.23	.6576	0.0001850	22.51	CONNECTOR BODY,ELEC	5935 00 378 0941
53	100	726.31	.6591	0.0001806	23.02	CONNECTOR RECEPTACL	5935 01 057 5009
54	66	767.66	.6628	0.0001374	30.09	SWITCH,SENSITIVE	5930 00 728 0562
55	101	795.72	.6653	0.0001355	30.38	ADAPTER,CABLE CLAMP	5935 01 086 7550
56	97	829.12	.6682	0.0001300	31.53	CONNECTOR PLUG,ELEC	5935 01 049 2241
57	14	874.88	.6721	0.0001240	32.87	CONNECTOR & HOLDER	4920 00 530 1473
58	78	905.76	.6746	0.0001232	32.98	CONNECTOR PLUG,ELEC	5935 00 501 1921
59	114	921.30	.6759	0.0001229	32.98	CONTACT,ELECTRICAL	5999 00 551 0835
60	89	1001.46	.6823	0.0001171	34.28	ADAPTER,CABLE CLAMP	5935 01 007 5788
61	52	1090.51	.6888	0.0001051	37.83	GASKET SET	5330 00 402 0204
62	3	1109.00	.6901	0.0001032	38.46	BUSHING SLV	3120 01 090 5601
63	98	1130.84	.6916	0.0000999	39.66	CONNECTOR,RECEPTACL	5935 01 051 1822
64	68	1150.23	.6929	0.0000985	40.15	CONNECTOR,RECEPTACL	5935 00 115 8549
65	59	1196.30	.6956	0.0000825	47.72	CIRCUIT BREAKER	5925 00 179 1202
66	99	1220.54	.6969	0.0000788	49.90	CONNECTOR,PLUG,ELEC	5935 01 057 4481
67	94	1252.41	.6982	0.0000599	65.48	CONNECTOR,RECEPTACL	5935 01 038 6492
68	2	1286.35	.6996	0.0000562	69.62	HOLDER ASY PUM	2910 00 780 0934
69	58	1326.02	.7009	0.0000481	81.20	CIRCUIT BREAKER	5925 00 103 5097
70	83	1367.96	.7022	0.0000455	85.68	CONNECTOR,PLUG,ELEC	5935 00 534 7877
71	60	1414.92	.7036	0.0000407	95.76	CIRCUIT BREAKER	5925 00 198 4131
72	74	1511.70	.7063	0.0000393	98.72	CONNECTOR,RECEPTACL	5935 00 374 7820
73	5	1610.54	.7090	0.0000385	100.49	FAN,TUBEAXIAL	4140 00 525 9214
74	61	1662.35	.7103	0.0000369	104.64	CIRCUIT BREAKER	5925 01 037 6875
75	63	1714.16	.7117	0.0000369	104.44	CIRCUIT BREAKER	5925 01 038 4066
76	64	1777.70	.7131	0.0000301	127.85	CIRCUIT BREAKER	5925 01 044 0307
77	79	1844.18	.7144	0.0000287	133.51	CONNECTOR RECEPTACL	5935 00 502 4828
78	62	1911.64	.7158	0.0000283	135.22	CIRCUIT BREAKER	5925 01 038 1357
79	80	2051.44	.7185	0.0000272	140.17	CONNECTOR BODY,RECE	5935 00 515 3587
80	91	2122.81	.7199	0.0000268	142.24	ADAPTER,CABLE CLAMP	5935 01 014 0396
81	133	2420.60	.7240	0.0000191	198.54	CIRCUIT CARD ASY	6625 01 017 4569
82	105	2727.57	.7201	0.0000185	203.33	RELAY,HYBRID	5945 01 021 1277
83	22	3577.32	.7391	0.0000174	212.78	CIRCUIT CARD ASY	4920 01 035 3333
84	16	4450.32	.7502	0.0000169	215.36	CIRCUIT CARD ASY	4920 01 004 2373
85	72	4597.94	.7520	0.0000166	218.85	CONNECTOR BODY,RECE	5935 00 328 2054
86	125	5198.81	.7577	0.0000125	208.36	POWER SUPPLY	6130 01 018 5990
87	137	6488.81	.7676	0.0000100	358.53	CIRCUIT CARD ASY	6625 01 060 1888
88	124	7969.81	.7789	0.0000098	357.44	POWER SUPPLY	6130 01 017 3598
89	69	8178.04	.7804	0.0000092	382.79	CONNECTOR BODY,PLUG	5935 00 146 4267
90	41	9757.04	.7907	0.0000082	420.50	CIRCUIT CARD ASY	4920 01 085 7658

91	11	11579.04	.8021	0.0000078	438.65	CIRCUIT CARD ASY	4920 00 352 2798
92	9	13502.08	.8130	0.0000069	485.69	SAMPLING HEAD	4920 00 339 3632
93	136	13797.11	.8145	0.0000065	519.81	COMPONENT,BOARD ASY	6625 01 055 6532
94	120	14181.11	.8163	0.0000057	590.77	POWER SUPPLY	6130 00 249 2772
95	46	16695.11	.8269	0.0000051	652.19	CIRCUIT CARD ASY	4920 01 092 5802
96	4	17076.83	.8284	0.0000050	661.25	FAN,VANEAXIAL	4140 00 525 3197
97	138	18650.83	.8347	0.0000048	685.71	CIRCUIT CARD ASY	6625 01 066 8995
98	21	20732.83	.8426	0.0000045	722.02	CIRCUIT CARD ASY	4920 01 021 9537
99	25	24784.83	.8568	0.0000041	781.34	CIRCUIT CARD ASY	4920 01 051 6583
100	121	25451.73	.8587	0.0000033	975.33	POWER SUPPLY	6130 00 361 7110
101	13	26040.02	.8603	0.0000032	981.28	CIRCUIT CARD ASY	4920 00 516 6854
102	131	27277.21	.8636	0.0000031	1032.57	LEAD,TEST	6625 00 359 1281
103	43	29206.21	.8686	0.0000029	1072.02	CIRCUIT CARD ASY	4920 01 086 3753
104	19	31451.41	.8735	0.0000025	1240.67	CIRCUIT CARD ASY	4920 01 018 9092
105	135	32963.41	.8768	0.0000025	1242.90	CIRCUIT CARD ASY	6625 01 045 4002
106	45	36935.41	.8856	0.0000025	1247.49	CIRCUIT CARD ASY	4920 01 090 5085
107	31	40004.41	.8923	0.0000025	1250.73	CIRCUIT CARD ASY	4920 01 063 1155
108	32	41602.60	.8957	0.0000024	1286.10	CIRCUIT CARD ASY	4920 01 063 3615
109	29	42600.30	.8974	0.0000019	1595.45	CIRCUIT CARD ASY	4920 01 063 0162
110	39	43650.16	.8991	0.0000018	1675.65	CIRCUIT CARD ASY	4920 01 084 6167
111	10	44710.54	.9008	0.0000018	1689.21	CIRCUIT CARD ASY	4920 00 348 5883
112	47	48202.27	.9060	0.0000016	1860.32	CIRCUIT CARD ASY	4920 01 095 8170
113	12	53760.10	.9141	0.0000016	1870.93	ELECTRONIC COMPON	4920 00 427 8009
114	44	55012.80	.9159	0.0000015	1962.84	CIRCUIT CARD ASY	4920 01 086 5301
115	28	56285.83	.9176	0.0000015	1990.88	DELAY LINE	4920 01 057 1642
116	20	57632.15	.9194	0.0000014	2101.48	CIRCUIT CARD ASY	4920 01 020 1635
117	8	65931.15	.9292	0.0000013	2310.71	CIRCUIT CARD ASY	4920 00 295 1152
118	17	67432.15	.9310	0.0000013	2313.69	CIRCUIT CARD ASY	4920 01 004 8568
119	37	68938.95	.9328	0.0000013	2318.19	CIRCUIT CARD ASY	4920 01 071 2780
120	33	73538.95	.9381	0.0000012	2390.50	POWER SUPPLY	4920 01 064 6199
121	40	75110.95	.9398	0.0000012	2400.32	CIRCUIT CARD ASY	4920 01 085 4209
122	26	76743.28	.9416	0.0000012	2487.68	CIRCUIT CARD ASY	4920 01 057 1154
123	35	78467.41	.9434	0.0000011	2622.57	CIRCUIT CARD ASY	4920 01 069 6638
124	38	81516.41	.9465	0.0000011	2713.13	POWER SUPPLY	4920 01 083 8366
125	30	83436.97	.9483	0.0000010	2906.30	CIRCUIT CARD ASY	4920 01 063 0429
126	15	89207.09	.9538	0.0000010	2920.25	ELECTRONIC COMPON	4920 00 563 9146
127	36	91160.96	.9556	0.0000010	2934.31	CIRCUIT CARD ASY	4920 01 070 0832
128	122	93635.96	.9577	0.0000009	3245.61	POWER SUPPLY	6130 00 365 4532
129	34	96010.96	.9595	0.0000008	3552.18	CIRCUIT CARD ASY	4920 01 066 0347
130	23	103172.74	.9650	0.0000008	3582.42	CIRCUIT CARD ASY	4920 01 050 2457
131	24	105747.74	.9668	0.0000007	3822.14	CIRCUIT CARD ASY	4920 01 050 6356
132	134	109047.74	.9687	0.0000006	4888.93	CIRCUIT CARD ASY	6625 01 044 3467
133	18	112449.74	.9705	0.0000006	5030.42	ELECTRON COMPONE	4920 01 005 3843
134	130	117985.75	.9724	0.0000003	8170.28	CIRCUIT CARD ASY	6625 00 349 3575
135	126	125562.75	.9745	0.0000003	9764.47	POWER SUPPLY	6130 01 033 9491
136	107	134337.75	.9764	0.0000002	12894.18	ELECTRON TUBE	5960 01 026 4666
137	123	145905.75	.9785	0.0000002	14846.73	POWER SUPPLY	6130 00 369 6617
138	27	183040.75	.9804	0.0000001	54358.37	POWER SUPPLY ASY	4920 01 057 1192
139	42	270253.94	.9841	0.0000000	63877.00	ANALYZER,TEST	4920 01 086 0487

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